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Regional Earthquake Hypocenter Location Using a Fuzzy Logic Algorithm Enhanced SEISMOS Program

by

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Introduction

The study area, the state of New Mexico and West Texas, is generally divided into four major geologic and physiographic provinces, the Colorado Plateau, the Basin and Range, the Rio Grande rift, and the Great Plains. The crustal structures beneath these geographic features are primarily determined by seismic profiling. However, a precise crustal model is not available.

To obtain accurate regional earthquake locations, we need correct phase readings, a physically reasonable model of the crustal structure and a sophisticated location program. These parameters are not totally independent, they affect each other in different ways. In the real world, one or more of these parameters which determine the earthquake locations may be wrong, and people have to correct the errors in hypocenters before reaching any interpretations on their distribution. Sometimes, we don't even recognize the errors.

The most generally identified phases of regional earthquakes are Pg and Sg phases which are direct waves from the hypocenter to the recording station. The amplitudes of Pg and Sg and other refracted or reflected phases are controlled by the structure along the ray path. Due to the constraints of the location program and the available structural data, people are unable to reproduce the correct arrival time of these phases.

The purpose of this paper is to demonstrate the fitness of the current half-space model for locating regional earthquakes. Furthermore, we are introducing a new algorithm, the Fuzzy Location Algorithm, to dramatically reduce erroneous results possible with the present location programs. In this study, the SEISMOS and Fuzzy/SEISMOS programs are tested with synthetic and real data for regional earthquakes within the area of interest.

Crustal Model

There have been several seismic crustal studies have been done in New Mexico since the 1950's using nuclear test or mining explosions (Toppozada, 1974; Singer, 1989). Interpretations of these seismic profiles has yielded crustal models for New Mexico, and demonstrate that no single model can represent the crustal structure for the state as a whole.

The current crustal model used for locating regional earthquakes is a half-space model with a Pg velocity of 6.15 km/s and Poisson's ratio of 0.256. This model has been applied to New Mexico regional earthquakes occurring after January 1, 1962. The reasons we keep using a half-space model for locating regional earthquakes are: 1) The direct Pg and Sg phases are the easiest recognized phases and have the highest amplitudes at all distances from the hypocenters. 2) Regional earthquakes usually occur beyond the critical distance of Pn phase but this phase is most often too weakly recorded to produce a reliable reading. The previous location program, the HYPO71 program, uses only first arrival phases to locate earthquakes, and therefore if Pn or Sn cannot be picked the station cannot be used. 3) The currently used location program, the SEISMOS program, is able to accommodate multiple phases. However, the change in crustal thickness over the state is large, ranging from 30 to 51 km, and this makes it unrealistic with one dimensional crustal models to use Pn phase to locate regional earthquakes.

Fuzzy Logic Location Algorithm

General Fuzzy Logic Theory

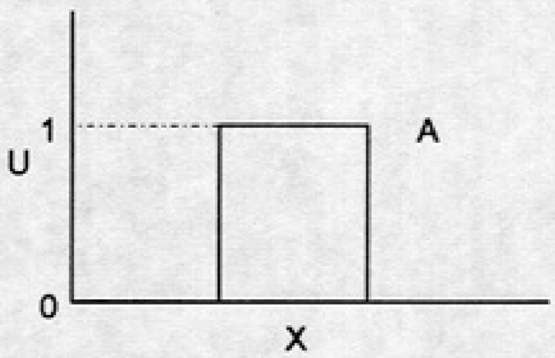
The theory of fuzzy logic deals with two problems: fuzzy set theory, which deals with the ambiguity found in semantics, and fuzzy measurement theory, which deals with the ambiguous nature of judgments and evaluations.

Fuzzy sets may be represented by a mathematical formulation often known as the membership function. This function gives a degree or grade of membership within the set. The membership function of a fuzzy set A, denoted by $\mu_A(x)$, maps the elements of the universe X into a numerical value within the range $[0,1]$, i.e.,

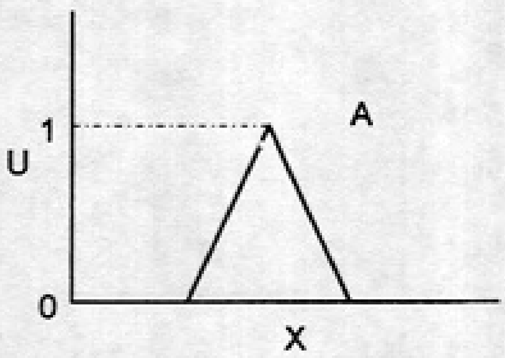
$$\mu_A(x) \in [0,1]$$

$$A = (x, \mu_A(x) | x \in X)$$

A simple graphical comparison of classic (or crisp) set theory and fuzzy set theory is shown below:



Membership function of crisp set A.



Membership function of fuzzy set A.

Let R and S be fuzzy relations on the Cartesian space X and Y. Then the following operations apply,

Union: $\mu_{R\cup S}(x,y)=\max(\mu_R(x,y),\mu_S(x,y))$

Intersection: $\mu_{R\cap S}(x,y)=\min(\mu_R(x,y),\mu_S(x,y))$

Complement: $\mu_{\bar{R}}(x,y)=1-\mu_R(x,y)$

Containment: $R\subset S\Rightarrow\mu_R(x,y)\le\mu_S(x,y)$

Fuzzy control systems are rule-based systems in which a set of so-called fuzzy rules represents a control decision mechanism to adjust the effects of certain causes coming from the system. The aim of fuzzy control systems is normally to substitute for or replace a skilled human operator with a fuzzy rule-based system. A fuzzy controller typically takes the form of a set of IF-THEN rules whose antecedents (IF part) and consequents (THEN part) are themselves membership functions. Consequents from different rules are numerically combined and are then collapsed to yield a single real-number output.

The input data, rules, and output action or consequence are generally fuzzy sets expressed by means of appropriate membership functions defined on a proper space. The method of evaluation of rules is known as approximate reasoning or interpolative reasoning, and is commonly represented by composition of fuzzy relations applied to a fuzzy relational equation. In the study, we consider a multi-input and single-output fuzzy system. The general form of fuzzy rule-based expert systems for a system with n fuzzy inputs and a single fuzzy output is shown as follows:

R^1: IF x_1 is A_1^1 AND x_2 is A_2^1 ... AND x_n is A_n^1 THEN y is B^1

R^2: IF x_1 is A_1^2 AND x_2 is A_2^2 ... AND x_n is A_n^2 THEN y is B^2

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R^r: IF x_1 is A_1^r AND x_2 is A_2^r ... AND x_n is A_n^r THEN y is B^r

A fuzzy system with two non-interactive inputs x_1 and x_2 and a single output y is described by the following:

IF x_1 is A_1^k AND x_2 is A_2^k THEN y^k is R^k for k= 1, 2, ..., r

Therefore, the Max.-Min. composition of the fuzzy system will turn out to be given by:

$$\mu_Y(y) = Max_k\{Max_{x_1 \in X_1}\{Max_{x_2 \in X_2}\{Min[\mu_{X_1}(x_1), \mu_{X_2}(x_2), \mu_{R^k}(x_1, x_2, y)]\}\}\}$$

For Max.-product technique, the aggregated output is given by:

$$\mu_Y(y) = Max_k\{Max_{x_1 \in X_1}\{Max_{x_2 \in X_2}\{\mu_{X_1}(x_1) \cdot \mu_{X_2}(x_2) \cdot \mu_{R^k}(x_1, x_2, y)\}\}\}$$

In order to find a sharp value for the aggregated output, some appropriate defuzzification technique could be employed, i.e.,

$$\bar{y} = DEFUZZ[\mu_Y(y)]$$

Two very simple graphical interpretations of Max.-Min and Max.-Product methods are illustrated in Figure 1 and 2, respectively.

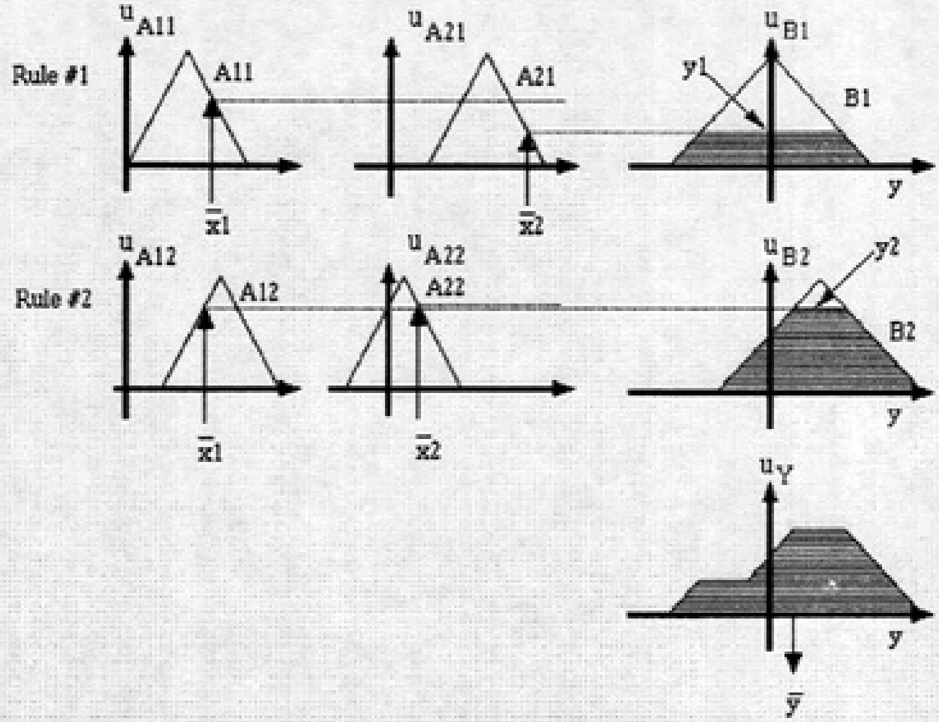

Figure 1. Graphical Max.-Min method

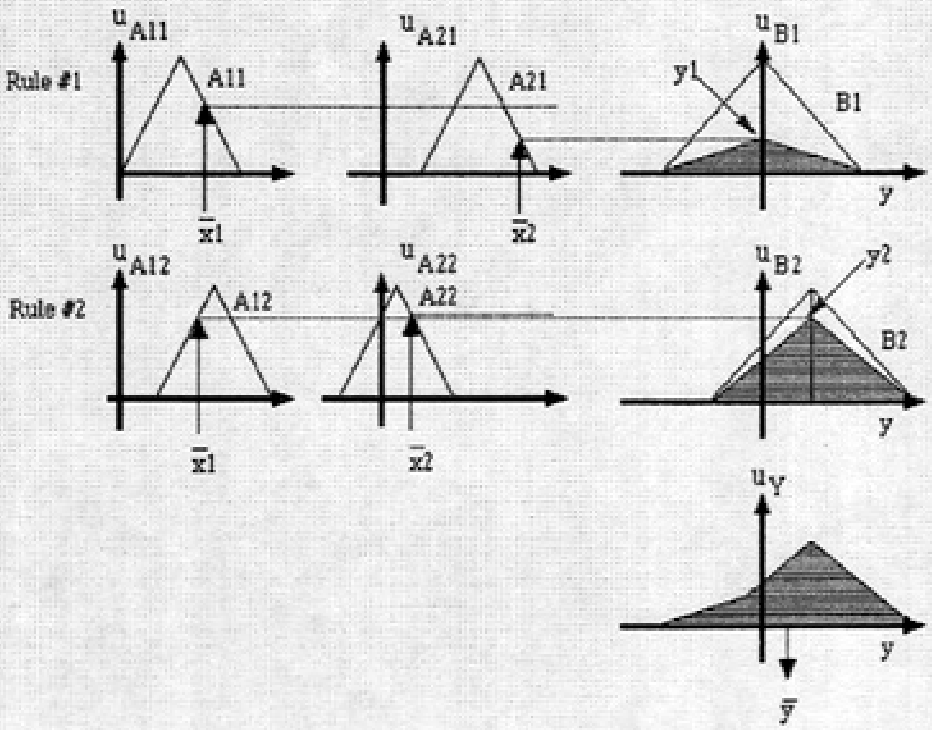

Figure 2. Graphical Max.-Product method

The defuzzification process is defined as the conversion of a fuzzy quantity, represented by a membership function, to a precise or crisp quantity. There are three commonly used techniques for defuzzification of fuzzy quantities: 1. Maximum method, 2. Centroid method and 3. Height method. I have selected the Centroid method as the defuzzification technique in the study. In this method of defuzzification, the weighted average of the membership function or the center of the gravity of the area bounded by the membership function curve is computed to be the most typical crisp value of the fuzzy quantity, i.e.,

$$\bar{y} = \frac{\sum \mu_Y(y) \cdot y \Delta y}{\sum \mu_Y(y) \Delta y}$$

(Jamshidi and others,1993; Yager and Zadeh,1992; Zadeh and Kacprzyk, 1992).

Application of Fuzzy Logic to Earthquake Location

The linear inversion method is the most commonly used method to achieve high-accuracy location of hypocenters of earthquakes. There are four hypocentral parameters (x, y, z, t), the spatial coordinates and the origin time, to be solved by this method. In the fuzzy logic approach, we are interested in improving the reliability of the location of epicenters for regional earthquakes. Hence, we fix the depth z at 10 km and reduce the hypocenter unknowns to the coordinates of the epicenter (x, y)(Uhrhammer, 1980).

In order to resolve the location of epicenters (x, y) of regional earthquakes, we employ a matrix of 40 by 40 grids with adjustable grid size. The initial matrix is centered at latitude 31° and longitude 106° and covers $9 \cdot 10^6$ km^2 with grid size 75 by 75 km. In addition, the initial crustal structure also differs from most locating programs. The half-space model that is discussed in the previous section is selected with a P wave velocity ranging from 5.9 km/s to 6.4 km/s and Poisson's ratio from 0.24 to 0.26. For each iteration, the center of the matrix and the grid size are redefined to reduce the survey area until the final location of the hypocenter is reached.

Weighting

Converting the quality of picked phases to fuzzy inputs, we assume the weights of the picked phases are linearly distributed, then these weightings can be directly mapped to fuzzy inputs. For example, there are 10 discrete weights in the SEISMOS location program, ranging from 0 to 9. The weighting 0 with uncertainty +/- 0.075 seconds is equivalent to fuzzy input 1 or totally true, the weighting 9 with uncertainty +/- infinity is equivalent to fuzzy input 0 or totally false.

Fuzzy Sets for Fuzzy Control System

There are four fuzzy sets involved in the fuzzy control system for locating earthquakes.

1. Pg phase correlation: The difference in travel time of Pg phases between any two selected stations must correlate with the distance of these two stations to the hypocenter. For example, if there are two stations A and B, the recorded arrival time difference must equal the actual travel time difference from the hypocenter to these two stations. Any trial hypocenter with theoretical travel time close to or equal to the observed travel time difference is likely to be the final location of hypocenter and

therefore the fuzzy output falls in range [0, 1]. On the contrary, trial hypocenters which have a mismatch between theoretical and actual travel time differences would have fuzzy outputs of zero.

2. Sg phase correlation: Same as above, except replacing Pg with Sg. The S wave velocity is calculated from the P wave velocities and Poisson's ratios and thus has a wider range than P wave velocity alone.
3. Pg and Sg travel time interval: The ray path distance calculated from the Pg and Sg arrivals at a single station must correlate to the distance between trial hypocenter and the station. This fuzzy set is valid only when both Pg and Sg phases are recorded at a single station. Any trial hypocenter with a distance close to or equal to the distance calculated by Pg and Sg phases is likely to be the final location of hypocenter and therefore the fuzzy output falls in the range [0, 1]. Conversely, trial hypocenters with distances much different from the calculated S-P distances would have fuzzy outputs of zero.
4. Travel time residual checksum: This fuzzy set checks out the trial hypocenter by verifying the travel time residuals between theoretical travel time from crustal model and observed travel time of all picked phases. It functions as a global adjuster of previous fuzzy summations. Two conditions must be fulfilled to be a qualified trial hypocenter, that is, a fuzzy output larger than 0. First, the travel time residuals of all picked phases must be within 5 seconds. Second, the travel time residuals of all picked phases must be normally distributed. This fuzzy set results from interactions of

all picked phases. And the most special feature of this fuzzy set is its global influence on the other fuzzy sets.

For an earthquake recorded by 10 seismic stations with both P and S phases, the fuzzy control system becomes 100 non-interactive inputs (45 P phase pairs, 45 S phase pairs, and 10 P and S travel time intervals) and one fuzzy output system. Therefore, the fuzzy control system may be expressed by:

$R^{1,1}$: IF x_1 is $A_1^{1,1}$ AND x_2 is $A_2^{1,1}$ ... AND x_{100} is $A_{100}^{1,1}$ THEN $y^{1,1}$ is $R^{1,1}$

$R^{1,2}$: IF x_1 is $A_1^{1,2}$ AND x_2 is $A_2^{1,2}$ ... AND x_{100} is $A_{100}^{1,2}$ THEN $y^{1,2}$ is $R^{1,2}$

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$R^{40,40}$: IF x_1 is $A_1^{40,40}$ AND x_2 is $A_2^{40,40}$ ... AND x_{100} is $A_{100}^{40,40}$ THEN $y^{40,40}$ is $R^{40,40}$

where $\mu_R(x_1, x_2, \ldots, x_{100}) = Min\{\mu_{A_1}(x_1), \mu_{A_2}(x_2), \ldots, \mu_{A_{100}}(x_{100})\}$

The Max.-Min. composition of the fuzzy system will turn out to be given by:

$$\mu_Y(\vec{y}) = \underset{i,j=1,40_{i,j}}{Max}\{\underset{n=1,100_{x_n \in X_n}}{Max}\{Min[\mu_{X_n}(x_n), \mu_{R^{i,j}}(x_n, \vec{y})]\}\}$$

The centroid defuzzification process of the above fuzzy control system will contain two parameters (x, y) corresponding to the coordinates of the earthquake, i.e.:

$$\bar{x} = \frac{\sum \mu_Y(\vec{y}) \cdot x \cdot \Delta x \cdot \Delta y}{\sum \mu_Y(\vec{y}) \cdot \Delta x \cdot \Delta y} \qquad \bar{y} = \frac{\sum \mu_Y(\vec{y}) \cdot y \cdot \Delta x \cdot \Delta y}{\sum \mu_Y(\vec{y}) \cdot \Delta x \cdot \Delta y}$$

The second iteration uses the fuzzy output $(\bar{x}, \bar{y})$ as the center of a new matrix with a reduced grid size. The process continues until the changes of fuzzy output are less than 2 km.

Sample Run of Fuzzy/SEISMOS Program

The Fuzzy/SEISMOS program is a refined SEISMOS program. It simply replaces the subroutine of SEISMOS which sets initial hypocenters with the Fuzzy Location Algorithm (FLA). Users would not find any differences between these two programs except the executing screen messages. The FLA adds the estimated initial hypocenters and the edge length of survey grid (total 40 by 40 grids) to the top of resolving process.

I have selected an event which occurred on March 5, 1994 for the test run of the Fuzzy/SEISMOS program. Figure 3 shows the screen messages of SEISMOS and Fuzzy/SEISMOS programs. On the left, SEISMOS took 6 iterations to reach the results. For the same event on the right, we have four columns of numbers after user input to the program's option. These four columns are x, y coordinates of SEISMOS program and grid length in x, y direction. The FLA subroutine was preset to escape at grid length less than 2 km. In this test case, the Fuzzy/SEISMOS program took only 4 rather than 6 iterations to solve the problem. The printouts of results of both programs are shown in Figure 4. SEISMOS and Fuzzy/SEISMOS programs show identical location of hypocenter and other statistic numbers (Hartse, 1991).

```
printout title:  SEISMOS program
*** working on event:  1


to estimate hypocenter manually type "1": 0
there are   9 data and   3 parameters

iteration  1 considering the case of  3 eigenvalues . . .

iteration  1 considering the case of  2 eigenvalues . . .

there are   9 data and   3 parameters

iteration  2 considering the case of  3 eigenvalues . . .

iteration  2 considering the case of  2 eigenvalues . . .

there are   9 data and   3 parameters

iteration  3 considering the case of  3 eigenvalues . . .

iteration  3 considering the case of  2 eigenvalues . . .

there are   9 data and   3 parameters

iteration  4 considering the case of  3 eigenvalues . . .

iteration  4 considering the case of  2 eigenvalues . . .

there are   9 data and   3 parameters

iteration  5 considering the case of  3 eigenvalues . . .

iteration  5 considering the case of  2 eigenvalues . . .

there are   9 data and   3 parameters

iteration  6 considering the case of  3 eigenvalues . . .
```

```
printout title: Fuzzy/SEISMOS program
to estimate hypocenter manually type "1":  0
Estimating event   1 location...
  600.000  100.0000  77  77
 -244.327  -108.606  38  38
  166.468   170.537  18  18
  411.465   265.188  9  9
  516.365   311.692  4  4
  542.788   312.961  2  2

*** working on event:  1


there are   9 data and   3 parameters

iteration  1 considering the case of  3 eigenvalues . . .

iteration  1 considering the case of  2 eigenvalues . . .

there are   9 data and   3 parameters

iteration  2 considering the case of  3 eigenvalues . . .

iteration  2 considering the case of  2 eigenvalues . . .

there are   9 data and   3 parameters

iteration  3 considering the case of  3 eigenvalues . . .

iteration  3 considering the case of  2 eigenvalues . . .

there are   9 data and   3 parameters

iteration  4 considering the case of  3 eigenvalues . . .
```

Figure 3. Screen messages of SEISMOS (left) and Fuzzy/SEISMOS (right) programs.

```
general iteration results for event    1:

itr        R          RMS
 1     65.573      22.134
 2      3.246       3.120
 3      1.118       0.837
 4      0.835       0.630
 5      0.841       0.630
 6      0.841       0.630
    year  month  day  hour  minute

    1994     3     5   12      36

 number of stations:  6   total number of picks:  9   number of reflections:  0

  starting hypocenter estimate: x= 392.99  y= 367.67  h=10.00  orig=39.92

  itr      x      adj        y      adj         h      adj        orig    adj       rms
   1    543.30 150.31    189.19-178.48      10.00    0.00       36.12   -3.79     22.13
   2    551.46   8.16    309.61 120.42      10.00    0.00       38.75    2.62      3.12
   3    582.96  31.50    321.86  12.25      10.00    0.00       39.64    0.90      0.84
   4    583.14   0.18    324.66   2.80      10.00    0.00       39.55   -0.10      0.63
   5    583.12  -0.02    324.63  -0.03      10.00    0.00       39.54   -0.01      0.63
   6    583.12   0.00    324.63   0.00      10.00    0.00       39.54    0.00      0.63


sta   phs fm qual   wt  delta  azm ain   obs-arv    obs-trv theo-trv  resid sta-cor
GDL2   s       5   0.72 160.9  101       37 25.80    46.26     45.76   -0.34   0.84
SMC    p       2   0.55 169.1  328  87   37  7.20    27.66     27.54   -0.34   0.46
SMC    s       6   0.17 169.1  328       37 28.60    49.06     48.09    0.17   0.80
CAR    p       3   0.18 174.4  339  87   37  9.30    29.76     28.40    1.06   0.30
CAR    s       6   0.31 174.4  339       37 30.30    50.76     49.60    0.64   0.52
BAR    p       1   0.20 192.0  344  87   37 10.90    31.36     31.26   -0.18   0.28
BAR    s       5   0.51 192.0  344       37 33.90    54.36     54.59   -0.71   0.49
LPM    p       3   0.11 209.3  345  87   37 13.00    33.46     34.08   -0.73   0.11
CPRX   p       5   0.26 211.3   73  87   37 15.30    35.76     34.40    0.85   0.51

  lat      1std     2std  rmatrx  rsubk      lon      1std     2std  rmatrx  rsubk
32 29.35  6.26    12.51  1.000   0.000  106  3.08  4.63     9.26  1.000   0.000

  depth   1std     2std  rmatrx  rsubk       orig    1std     2std  rmatrx  rsubk
  10.00   0.00     0.00  1.000   0.000       39.54   0.86     1.72  0.000   0.000

 1std epi  2std epi   rms    gap    dmag    nmag
   7.78     15.57    0.63   226    0.81      2
```

```
general iteration results for event    1:

itr        R          RMS
 1      3.167       0.952
 2      0.832       0.629
 3      0.841       0.630
 4      0.841       0.630
    year  month  day  hour  minute

    1994     3     5   12      36

 number of stations:  6   total number of picks:  9   number of reflections:  0

  starting hypocenter estimate: x= 542.79  y= 312.96  h=10.00  orig=39.92

  itr      x      adj       y      adj        h      adj       orig    adj       rms
   1    582.54  39.75   320.26    7.30     10.00    0.00     39.53   -0.39     0.95
   2    583.14   0.60   324.68    4.42     10.00    0.00     39.55    0.03     0.63
   3    583.12  -0.02   324.63   -0.05     10.00    0.00     39.54   -0.01     0.63
   4    583.12   0.00   324.63    0.00     10.00    0.00     39.54    0.00     0.63


sta   phs fm qual   wt  delta  azm ain   obs-arv    obs-trv theo-trv  resid sta-cor
GDL2   s       5   0.72 160.9  101       37 25.80    46.26     45.76   -0.34   0.84
SMC    p       2   0.55 169.1  328  87   37  7.20    27.66     27.54   -0.34   0.46
SMC    s       6   0.17 169.1  328       37 28.60    49.06     48.09    0.17   0.80
CAR    p       3   0.18 174.4  339  87   37  9.30    29.76     28.40    1.06   0.30
CAR    s       6   0.31 174.4  339       37 30.30    50.76     49.60    0.64   0.52
BAR    p       1   0.20 192.0  344  87   37 10.90    31.36     31.26   -0.18   0.28
BAR    s       5   0.51 192.0  344       37 33.90    54.36     54.59   -0.71   0.49
LPM    p       3   0.11 209.3  345  87   37 13.00    33.46     34.08   -0.73   0.11
CPRX   p       5   0.26 211.3   73  87   37 15.30    35.76     34.40    0.85   0.51

  lat      1std     2std  rmatrx  rsubk      lon      1std     2std  rmatrx  rsubk
32 29.35  6.26    12.51  1.000   0.000  106  3.08  4.63     9.26  1.000   0.000

  depth   1std     2std  rmatrx  rsubk       orig    1std     2std  rmatrx  rsubk
  10.00   0.00     0.00  1.000   0.000       39.54   0.86     1.72  0.000   0.000

 1std epi  2std epi   rms    gap    dmag    nmag
   7.78     15.57    0.63   226    0.81      2
```

Figure 4. Printouts of the sample event of SEISMOS (left) and Fuzzy/SEISMOS (right) programs. These two programs have the same printout format.

Test Procedure

The purpose of the test procedure is to find out the capabilities of the SEISMOS and the Fuzzy/SEISMOS programs. The later program is a modified SEISMOS program with the enhanced FLA used as a subroutine for initial hypocenter estimation. I have used synthetic arrival time data in addition to observed arrival time data to test the performance of these two programs. The test results provide a way to map the stability of epicenters of regional earthquakes located with different station geometries.

The synthetic data is designed to test the stability of results of hypocentral locations reached by the two location programs under different station geometry conditions. These conditions are: 1) the number of available seismic-station readings, 2) changes in the crustal model, velocities and Poisson's ratio, and 3) the uncertainties of the input phase readings. For each test case, 72 synthetic pick files were used as input to the SEISMOS and Fuzzy/SEISMOS programs. The 72 pick files were for events distributed more or less evenly over the study area. Station readings in the synthetic data consist of perfect Pg and Sg phases with weightings of 2 and 5, respectively. Under these ideal conditions, the difference between the hypocenter yielded by the location program from the true location should be zero. Thus, the stability for the synthetic data case is measured by the differences in hypocenter location.

For each test case, we evaluate the stability of the hypocentral location by changing only one condition. In the first synthetic data test, recorded seismic stations are randomly selected from two networks, Socorro local and WIPP networks. The designated number of available seismic stations are 3, 4, 5, and all of the local or WIPP network. In the second synthetic data test, synthetic data are generated with crustal velocities ranging from 5.95 km/s to 6.35 km/s and then solved by locating programs with a fixed crustal velocity of 6.15 km/s. In the third synthetic data test, the test procedure is the same as the second test except Poisson's ratio ranges from 0.24 to 0.26, and then is compared to model with a ratio of 0.25. The last synthetic data test case is a test of the effect of uncertainties in phase readings. For this test a random number between ± 0.50 seconds is added to every perfect phase reading before the data are entered into the location programs.

The observed arrival time data come from moderately strong local or regional earthquakes recorded by three or more stations in the WIPP and local networks. This test assumes that the location obtained from all recorded arrivals is more accurate than that obtained from readings from a single network. The all station location is used as the standard and is compared to locations obtained from single network data using both the SEISMOS and Fuzzy/SEISMOS programs. I selected seven events recorded between January, 1993 and June, 1994 to perform the test.

Location Program Performance

The location program performance under various test condition is illustrated in this section. Since we fixed all parameters except the test parameter, the test results show the best results people could expect with the programs. Any real world events similar to the test cases will have larger errors than the test events. For example, Figure 5 shows deviations between the hypocenters obtained by SEISMOS using perfect data and the synthetic hypocenters.

Two Networks with All Stations Recording. Both SEISMOS and Fuzzy/SEISMOS programs solve all 72 synthetic events with 16 station readings and generate the same results (Figure 5). The maximum error in the study area is 0.26 km.

Single Network with All Stations Recording. Both SEISMOS and Fuzzy/SEISMOS programs give the same results when Socorro only stations are used or WIPP only stations are used (Figures 6 and 7). The results for WIPP only stations have larger errors in north-east New Mexico than results for Socorro only stations.

Single Network with Five Stations Recording. For any five station Socorro network, both SEISMOS and Fuzzy/SEISMOS programs give the same results (Figures 8 through 10). However, different station configurations can produce different hypocentral deviations. For some WIPP five station configurations, SEISMOS and Fuzzy/SEISMOS

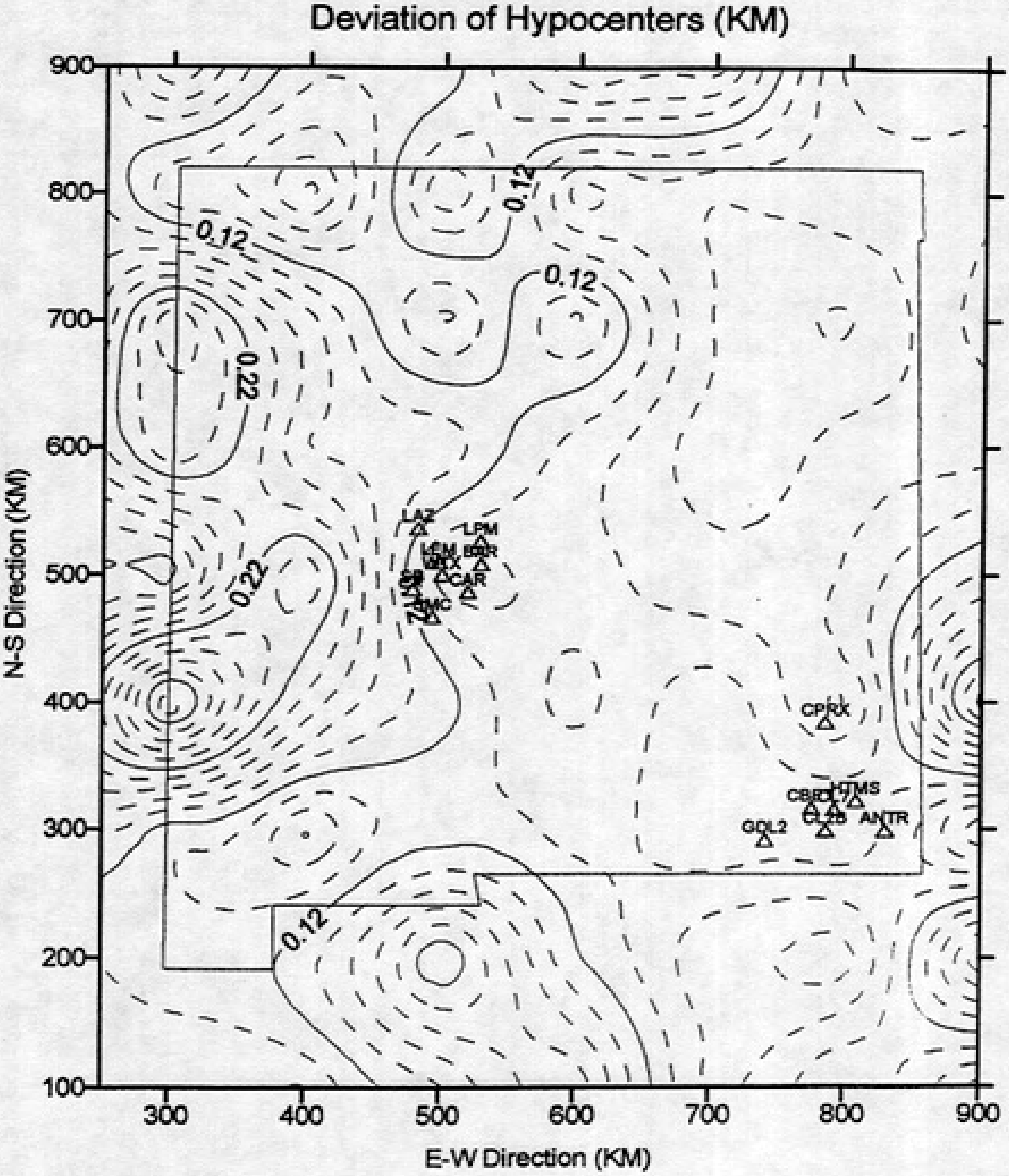

Figure 5. The deviation (in km) of hypocenters of location program from synthetic hypocenters. All WIPP and Socorro seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

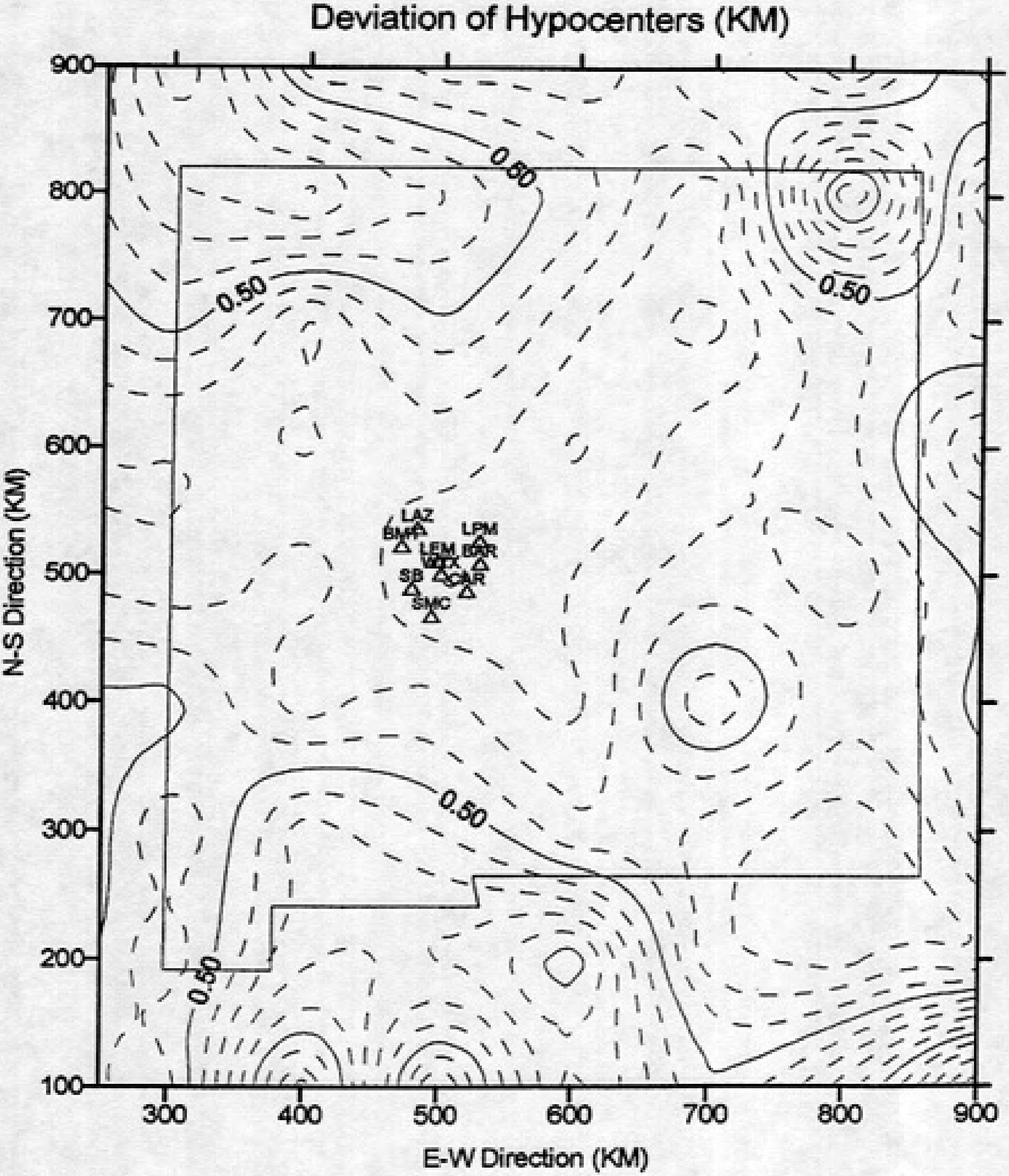

Figure 6. The deviation (in km) of hypocenters of location program from synthetic hypocenters. All Socorro local seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

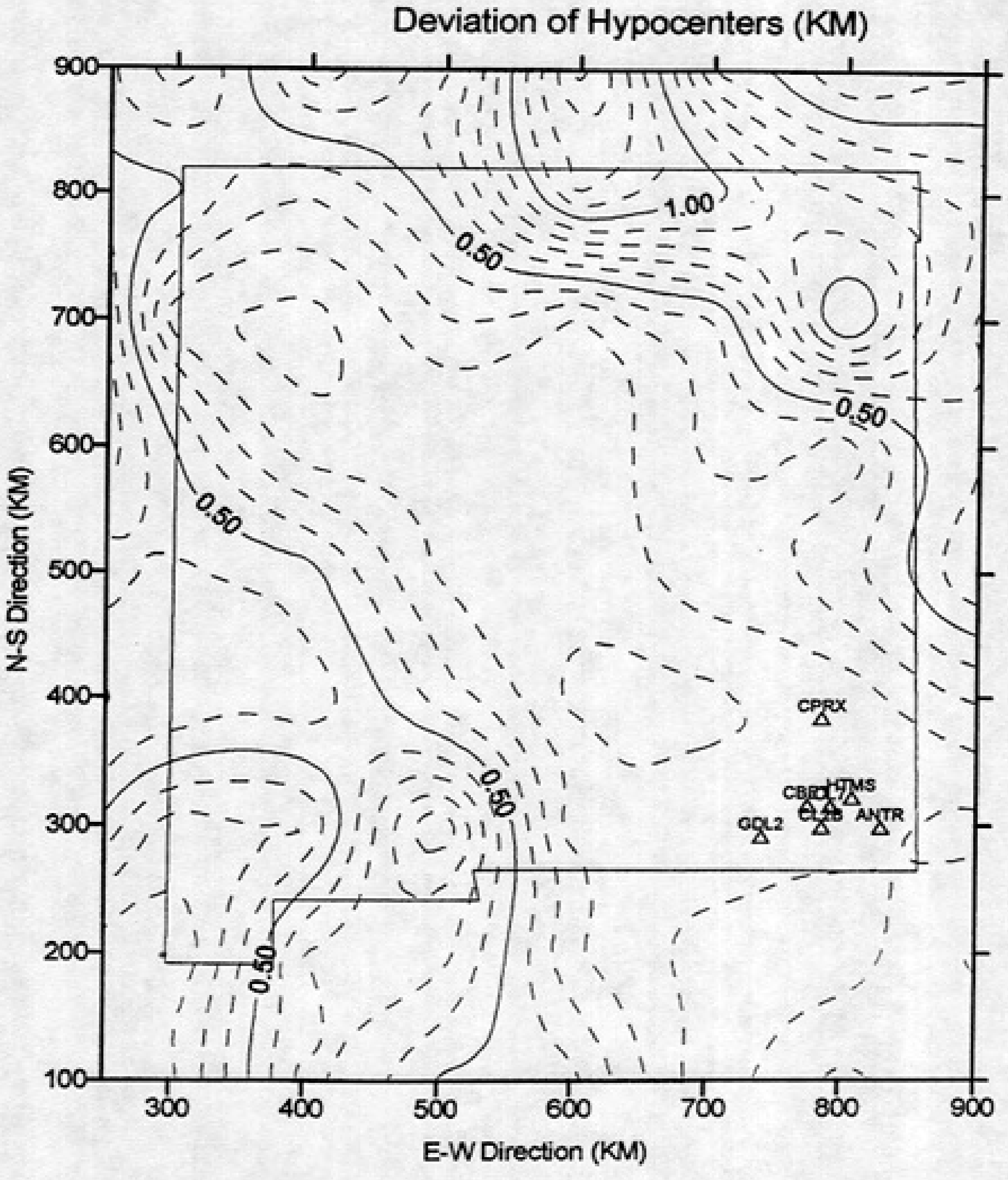

Figure 7. The deviation (in km) of hypocenters of location program from synthetic hypocenters. All WIPP seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

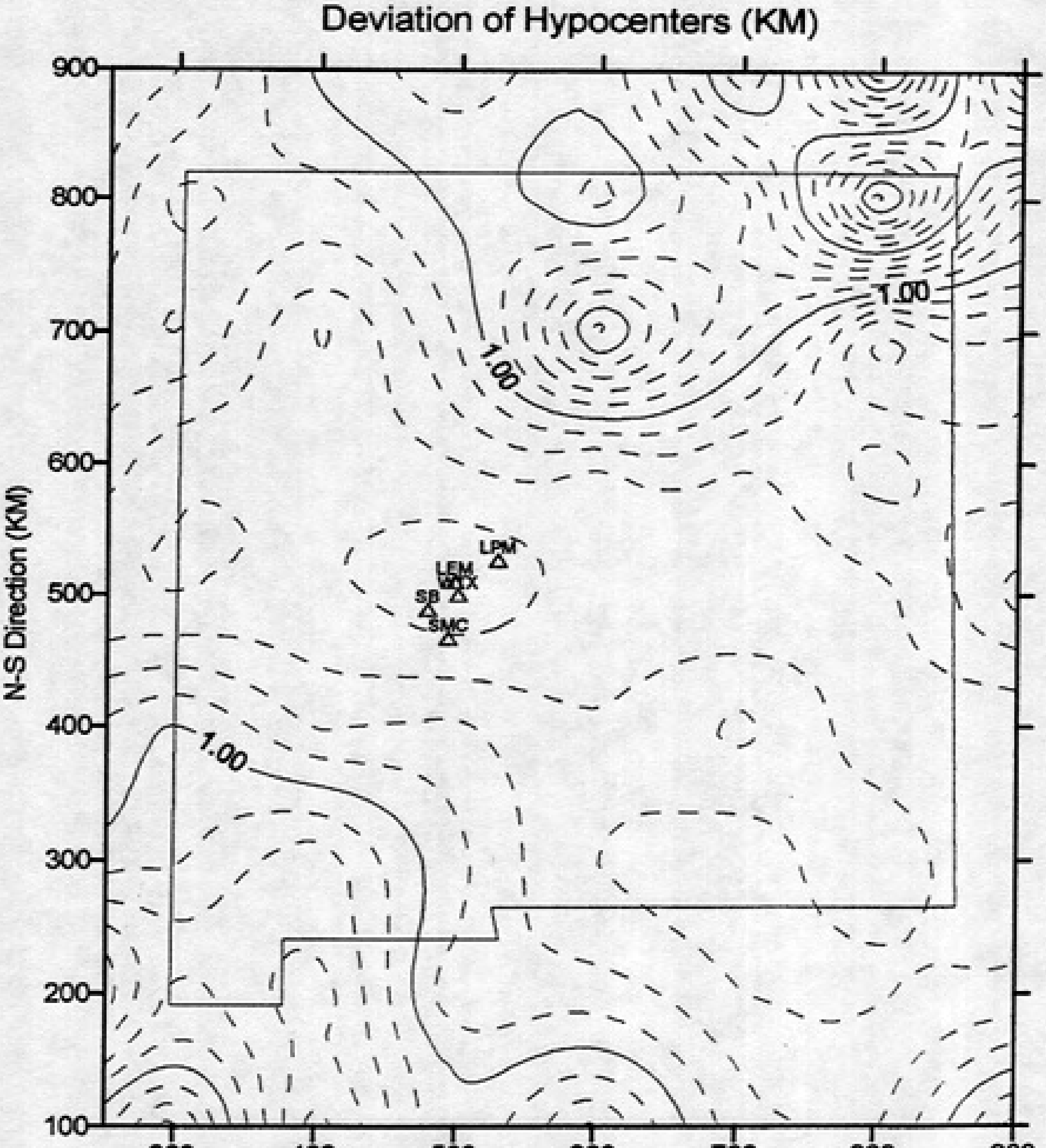

Figure 8. The deviation (in km) of hypocenters of location program from synthetic hypocenters. LEM, LPM, SB, SMC, and WTX of Socorro seismic network are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

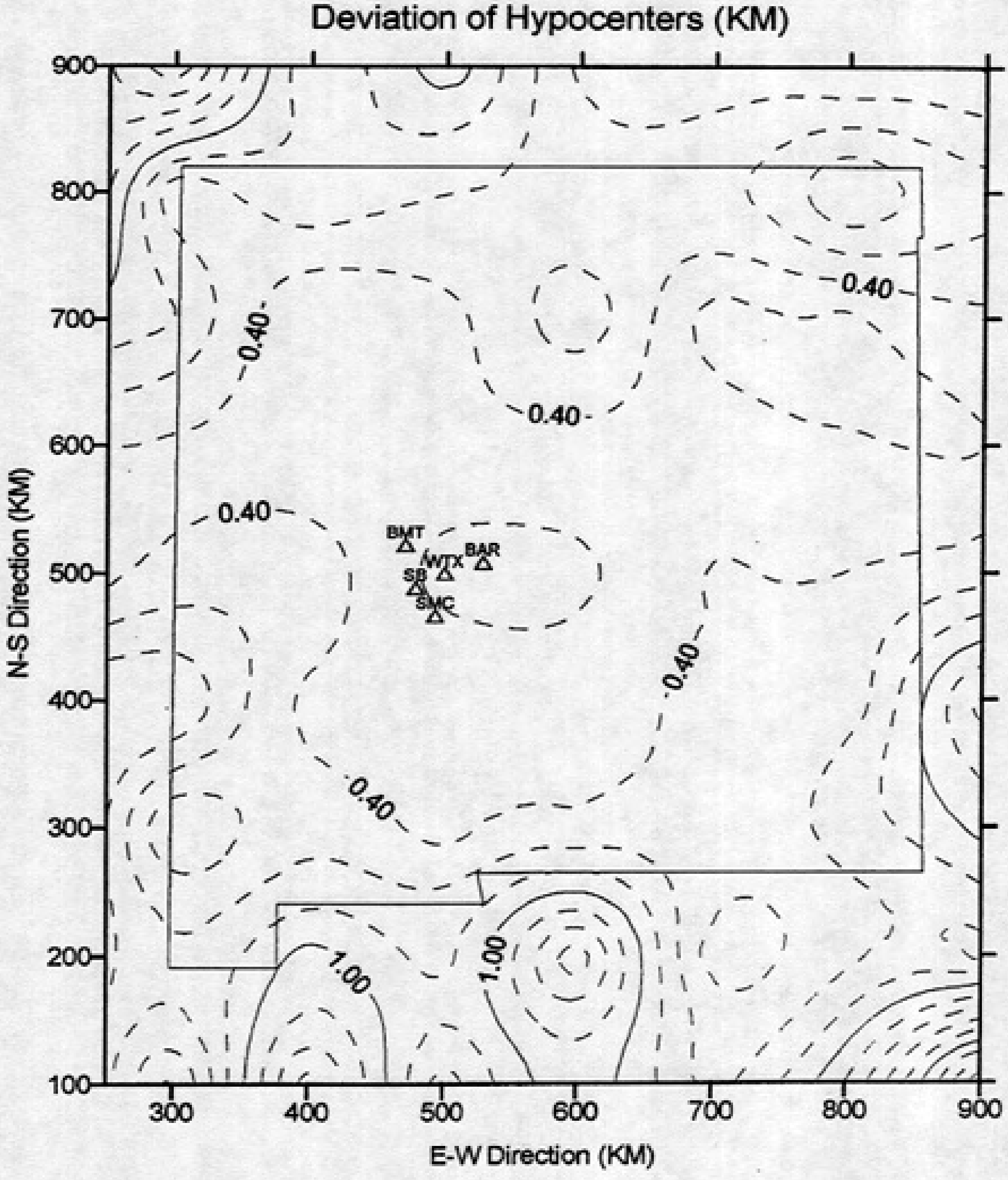

Figure 9. The deviation (in km) of hypocenters of location program from synthetic hypocenters. BAR, BMT, SB, SMC, and WTX of Socorro seismic network are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

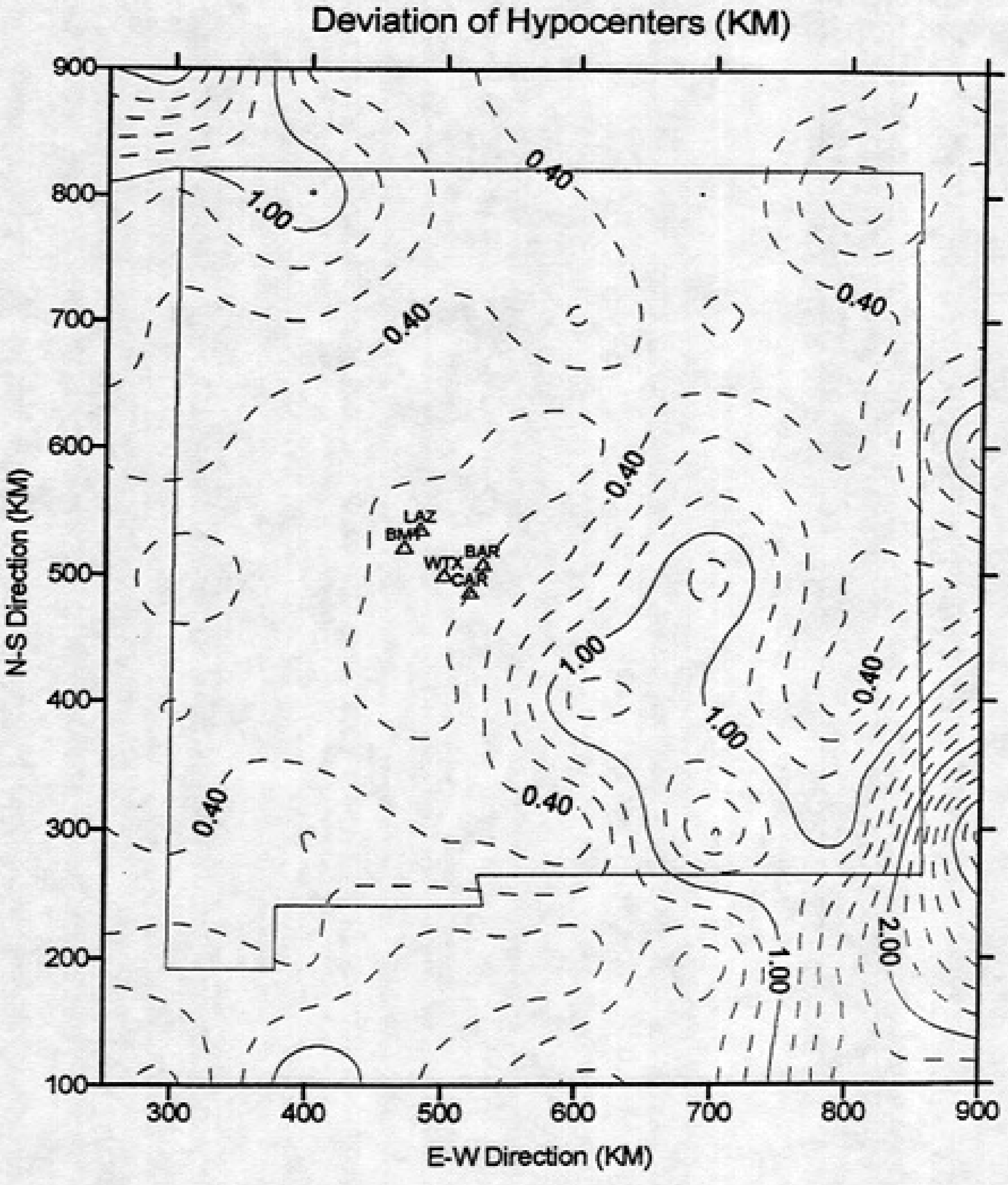

Figure 10. The deviation (in km) of hypocenters of location program from synthetic hypocenters. BAR, BMT, CAR, LAZ, and WTX of Socorro seismic network are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

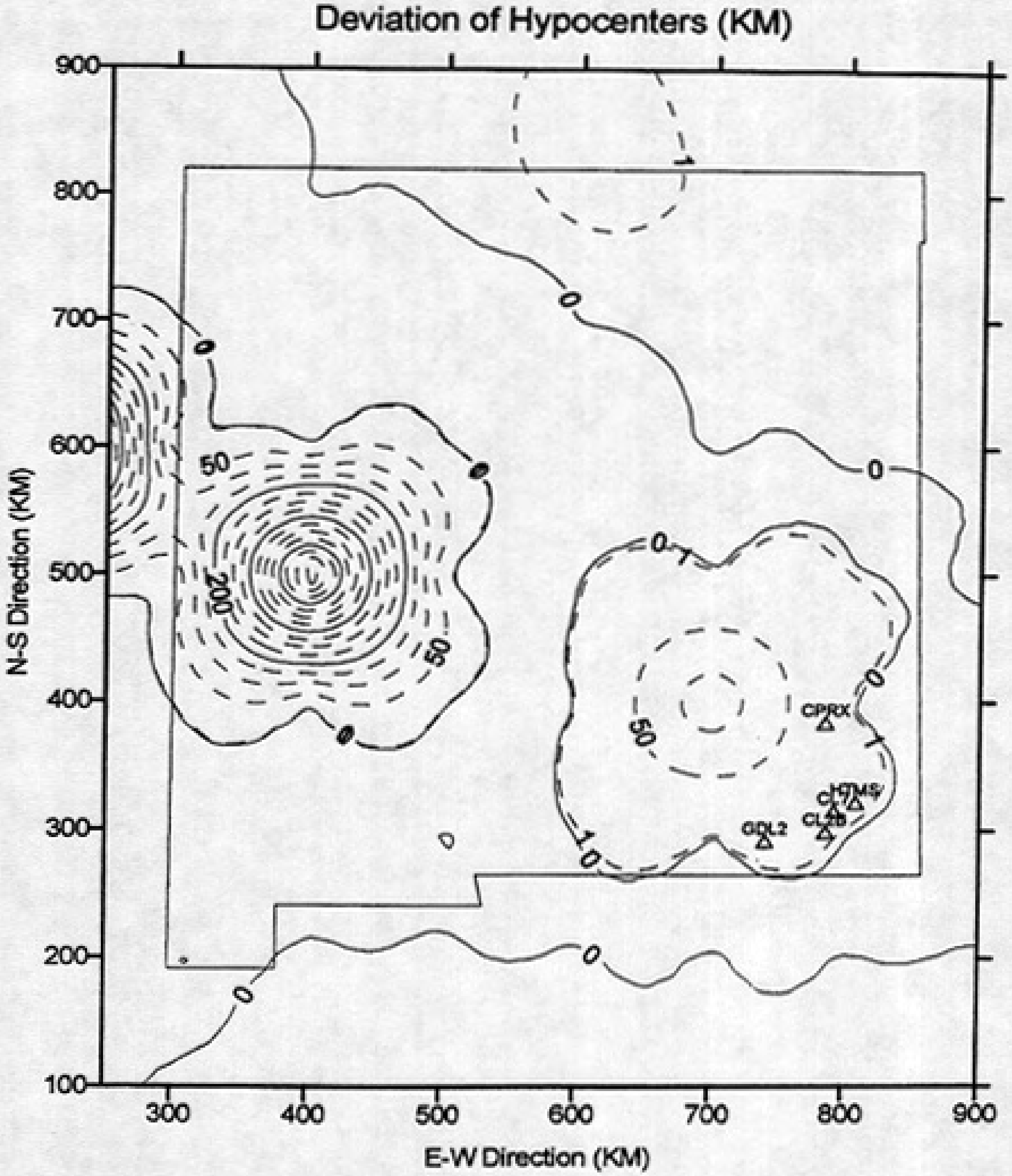

Figure 11a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. CL2B, CL7, CPRX, GDL2, and HTMS of WIPP seismic network are used.

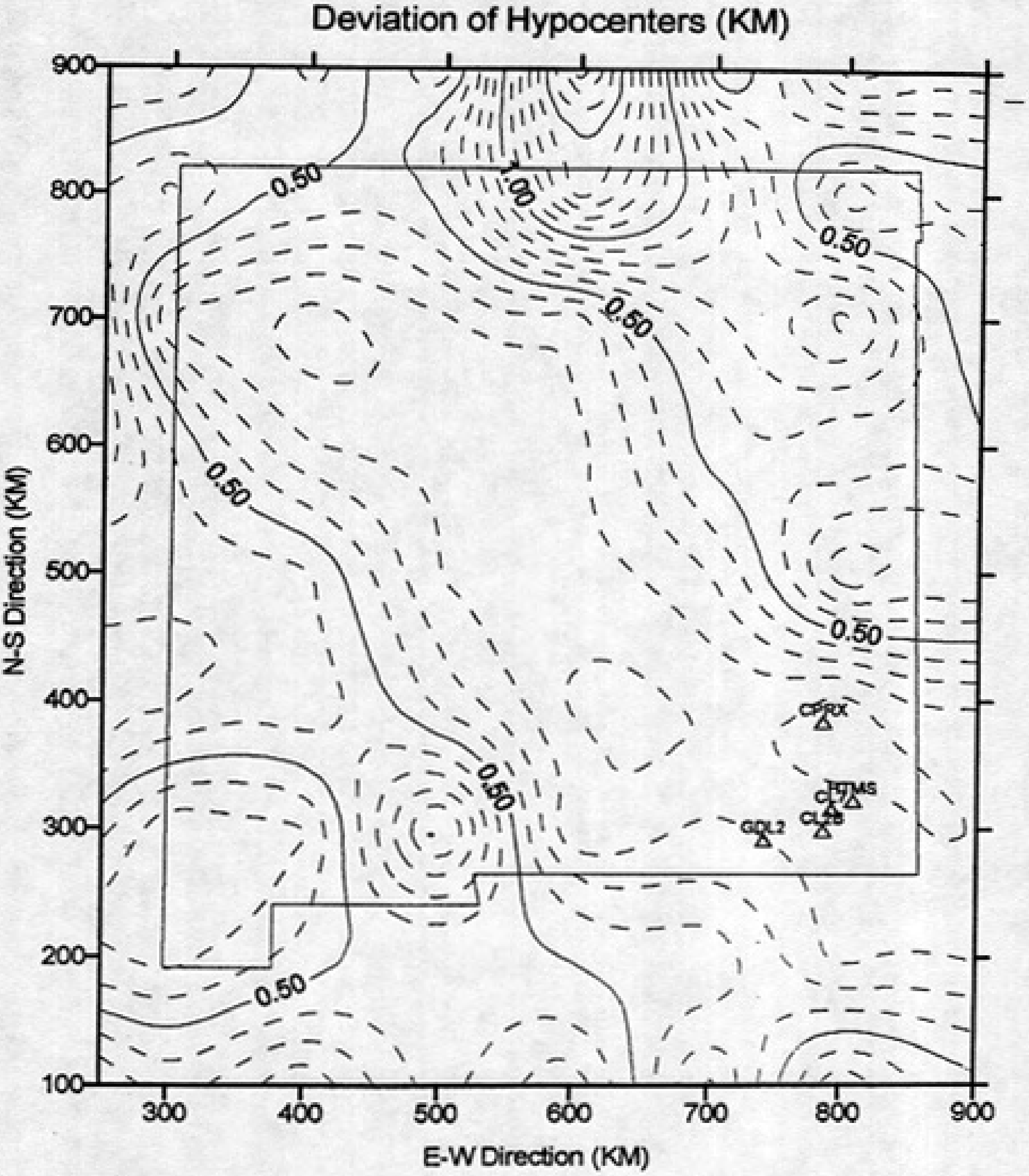

Figure 11b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. CL2B, CL7, CPRX, GDL2, and HTMS of WIPP seismic network are used.

do not give the same results. Figure 11a and 11b shows results for the five station WIPP network of stations CL2B, CL7 CPRX, GDL2 and HTMS. There are three test spots where the SEISMOS program cannot obtain a good estimate of the true hypocenter. The Fuzzy/SEISMOS program eliminates the problem areas. For the five station WIPP network of stations ANTR, CBET CL2B, CL7, and HTMS, the SEISMOS program produces locations with large deviations from true location in the east of New Mexico (Figure 12a). The Fuzzy/SEISMOS program eliminates this problem area. For the five station WIPP network of stations ANTR, CBET, CPRX, GDL2, and HTMS, both SEISMOS and Fuzzy/SEISMOS produce the same results (Figure 13).

Single Network with Four Stations Recording. For the four station Socorro network configurations tested, both SEISMOS and Fuzzy/SEISMOS programs produced the same results (Figures 14 through 16). However, as expected the most linear of the four station configurations (Figure 14) produced the largest differences between calculated and synthetic hypocenters. All three of the four station WIPP network configurations tested demonstrated that the SEISMOS program could not correctly locate earthquakes over 5 to 50 percent of the study area (Figures 17a through 19a). On the other hand, the Fuzzy/SEISMOS program satisfactorily located the synthetic events with the three four station WIPP networks tested (Figures 17b through 19b).

Single Network with Three Stations Recording. Three stations is the minimum number that can be used to locate an earthquake if depth is specified. For the three station

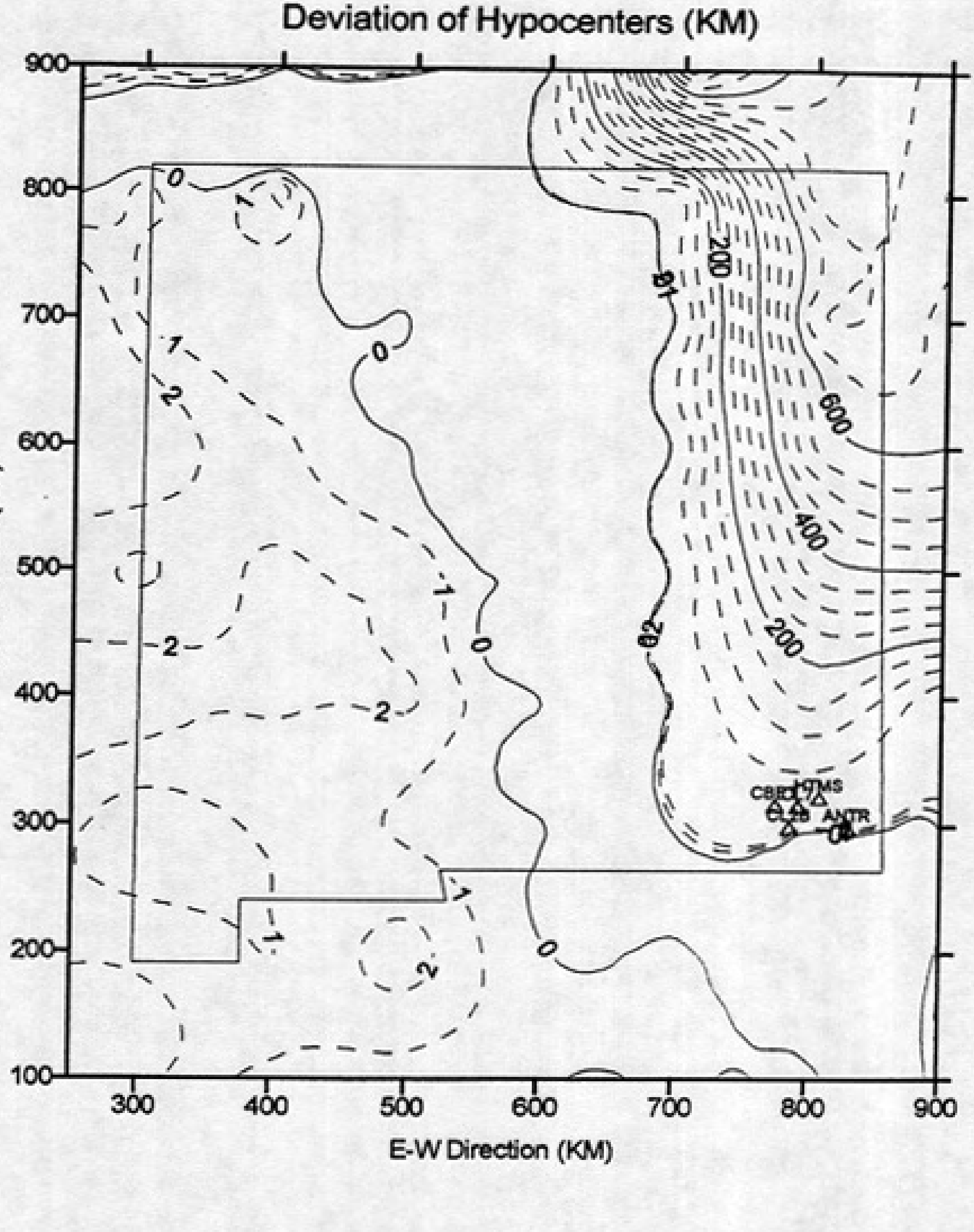

Figure 12a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. ANTR, CBET, CL2B, CL7, and HTMS of WIPP seismic network are used.

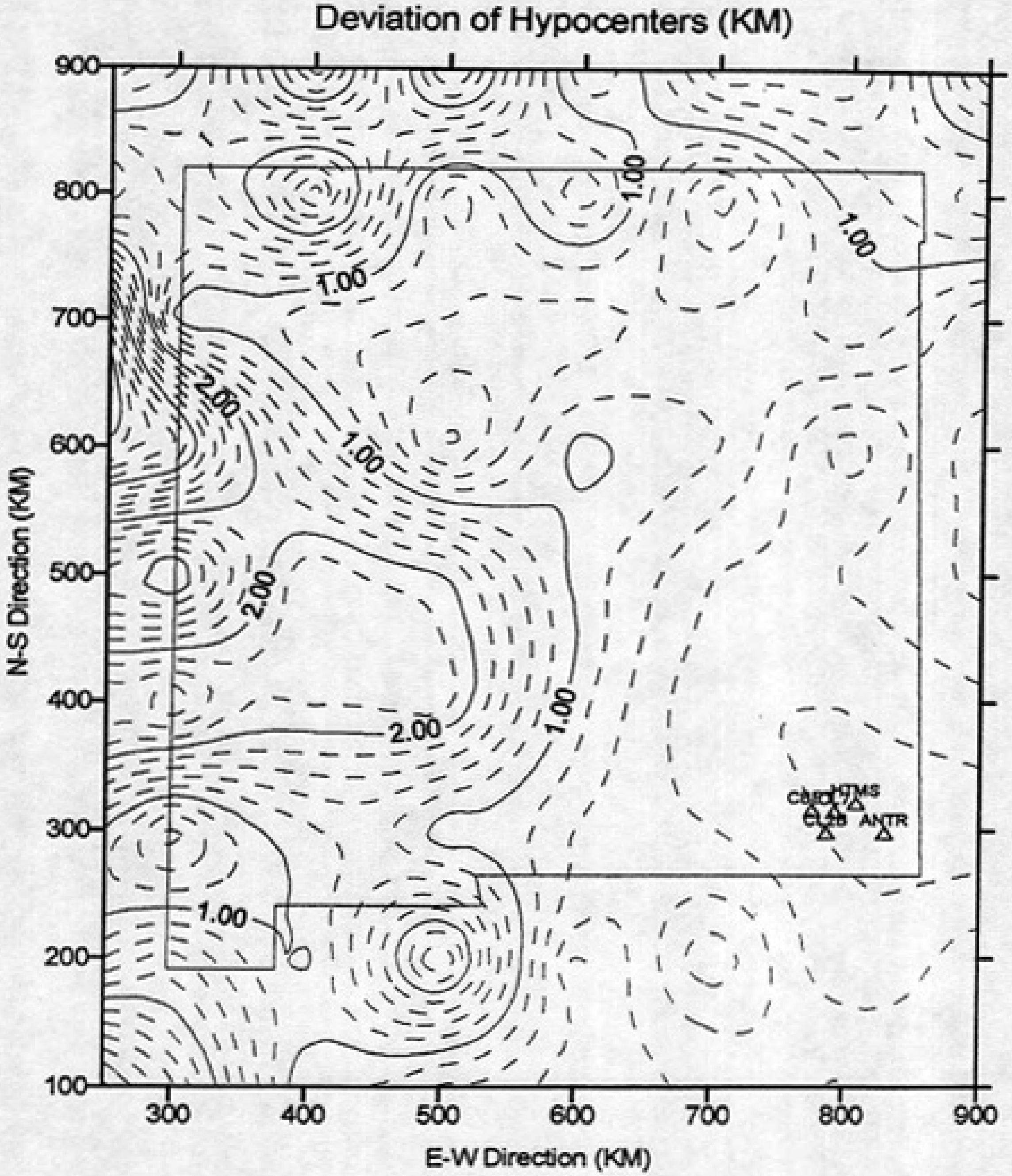

Figure 12b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. ANTR, CBET, CL2B, CL7, and HTMS of WIPP seismic network are used.

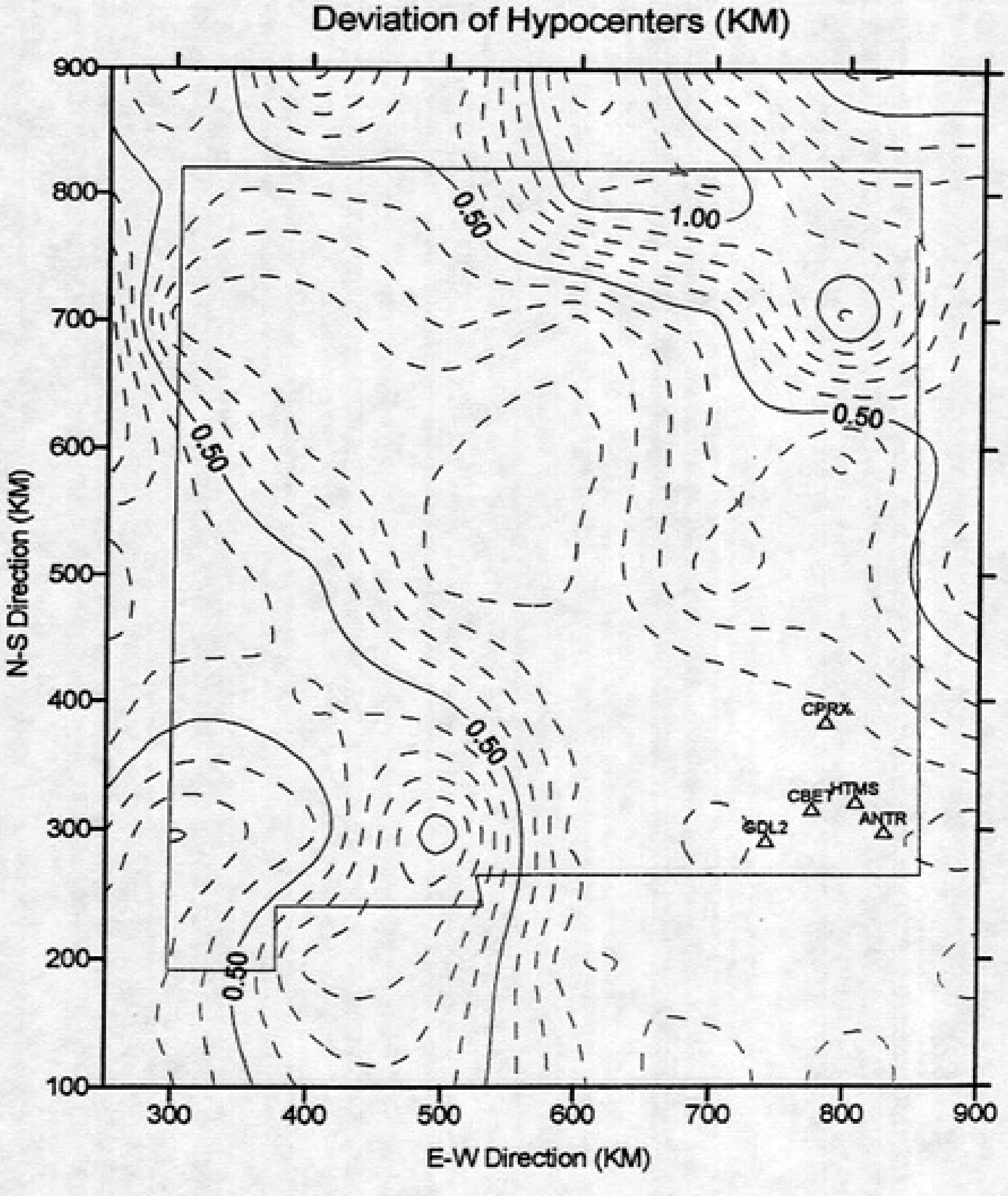

Figure 13. The deviation (in km) of hypocenters of location program from synthetic hypocenters. ANTR, CBET, CPRX, GDL2, and HTMS of WIPP seismic network are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

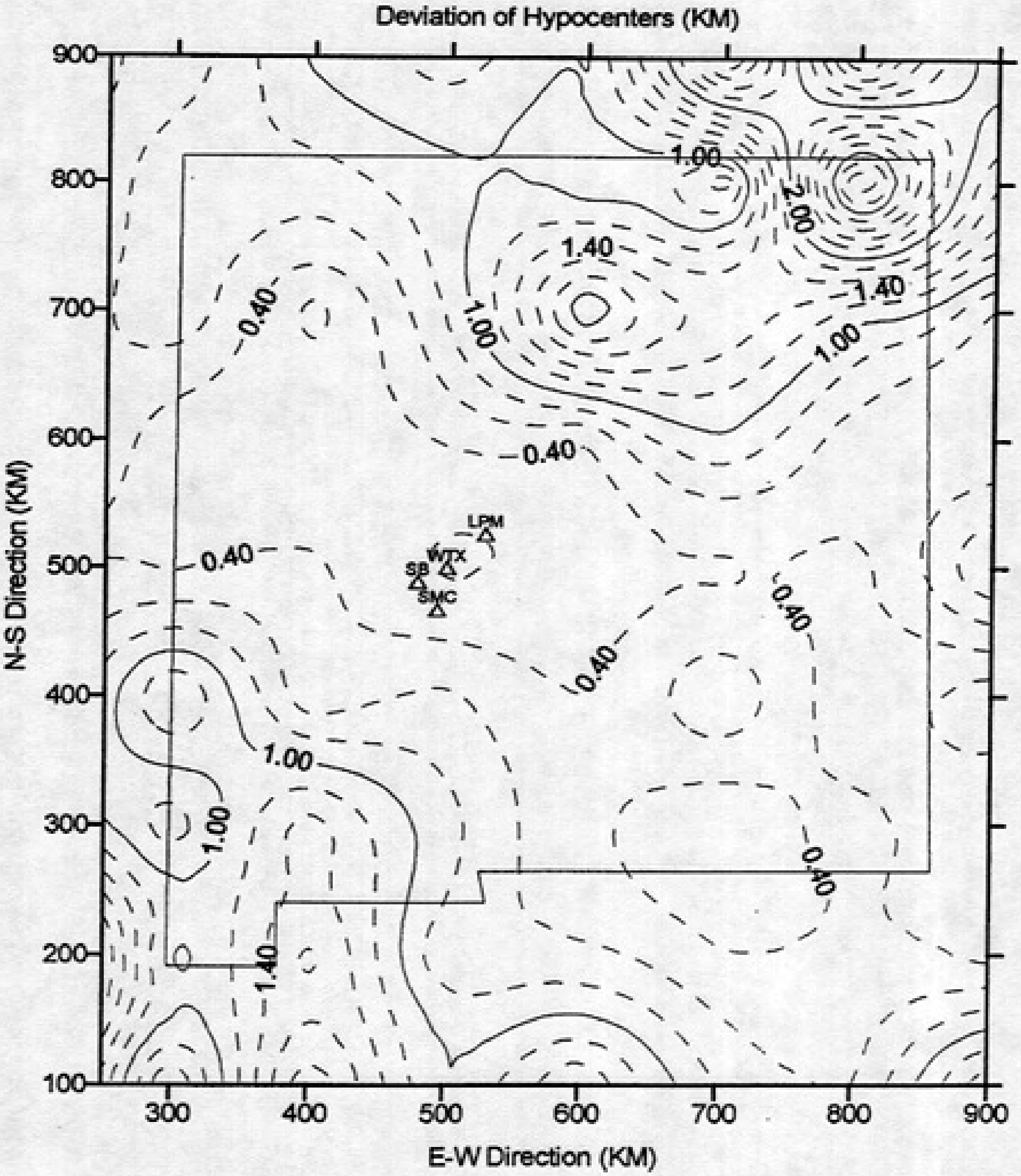

Figure 14. The deviation (in km) of hypocenters of location program from synthetic hypocenters. LPM, SB, SMC, and WTX of Socorro seismic network are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

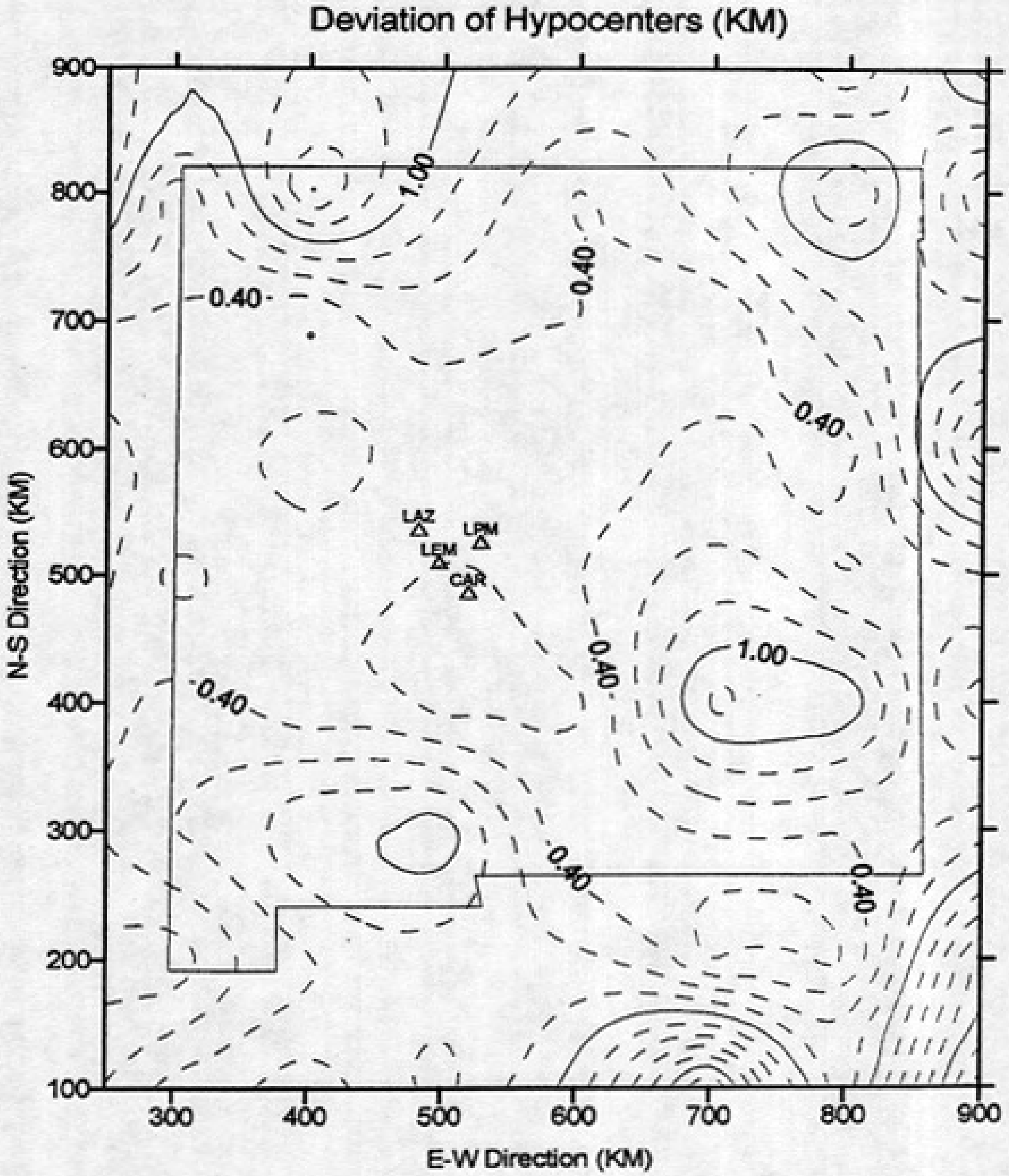

Figure 15. The deviation (in km) of hypocenters of location program from synthetic hypocenters. CAR, LAZ, LEM, and LPM of Socorro seismic network are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

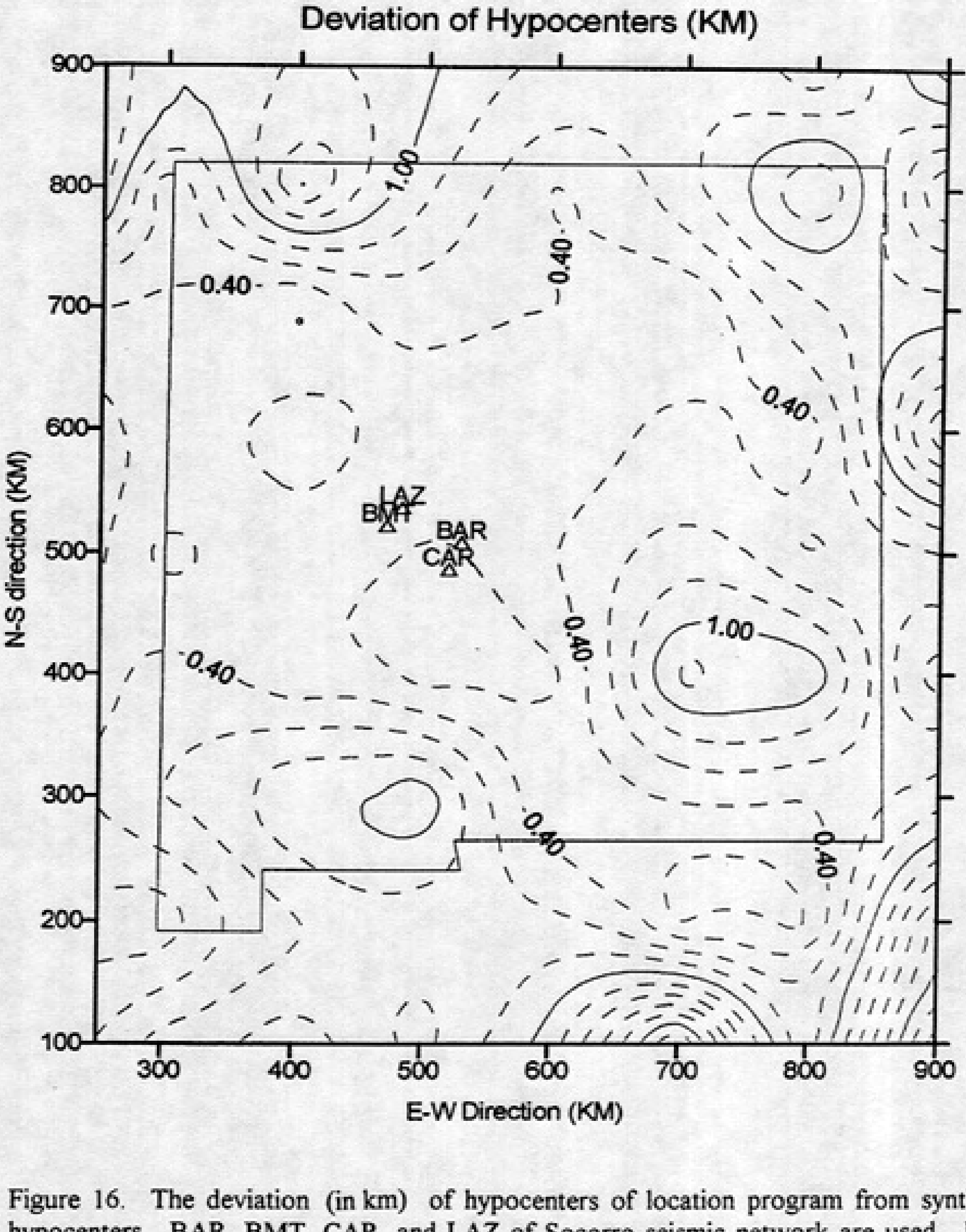

Figure 16. The deviation (in km) of hypocenters of location program from synthetic hypocenters. BAR, BMT, CAR, and LAZ of Socorro seismic network are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

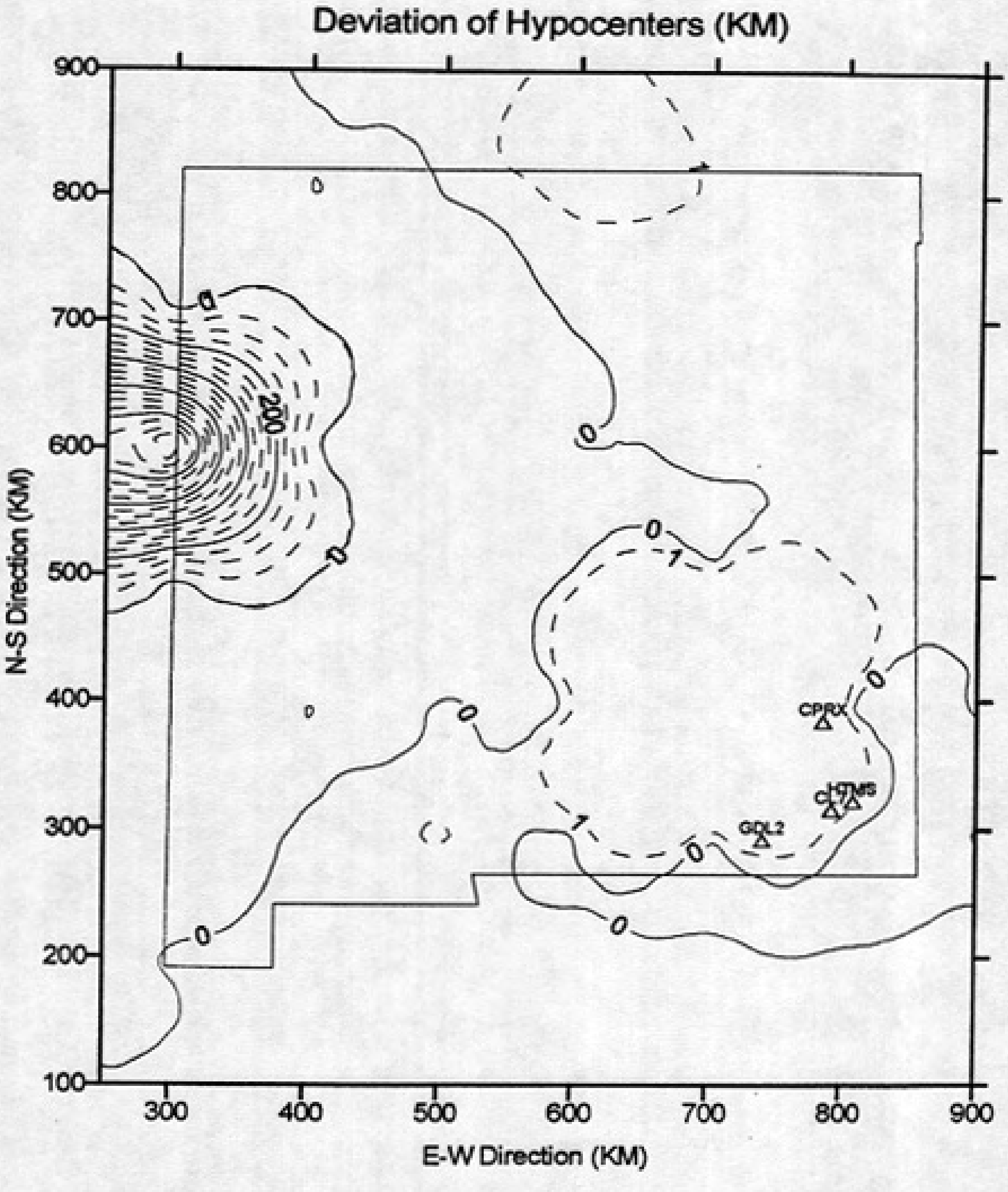

Figure 17a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. CL7, CPRX, GDL2, and HTMS of WIPP seismic network are used.

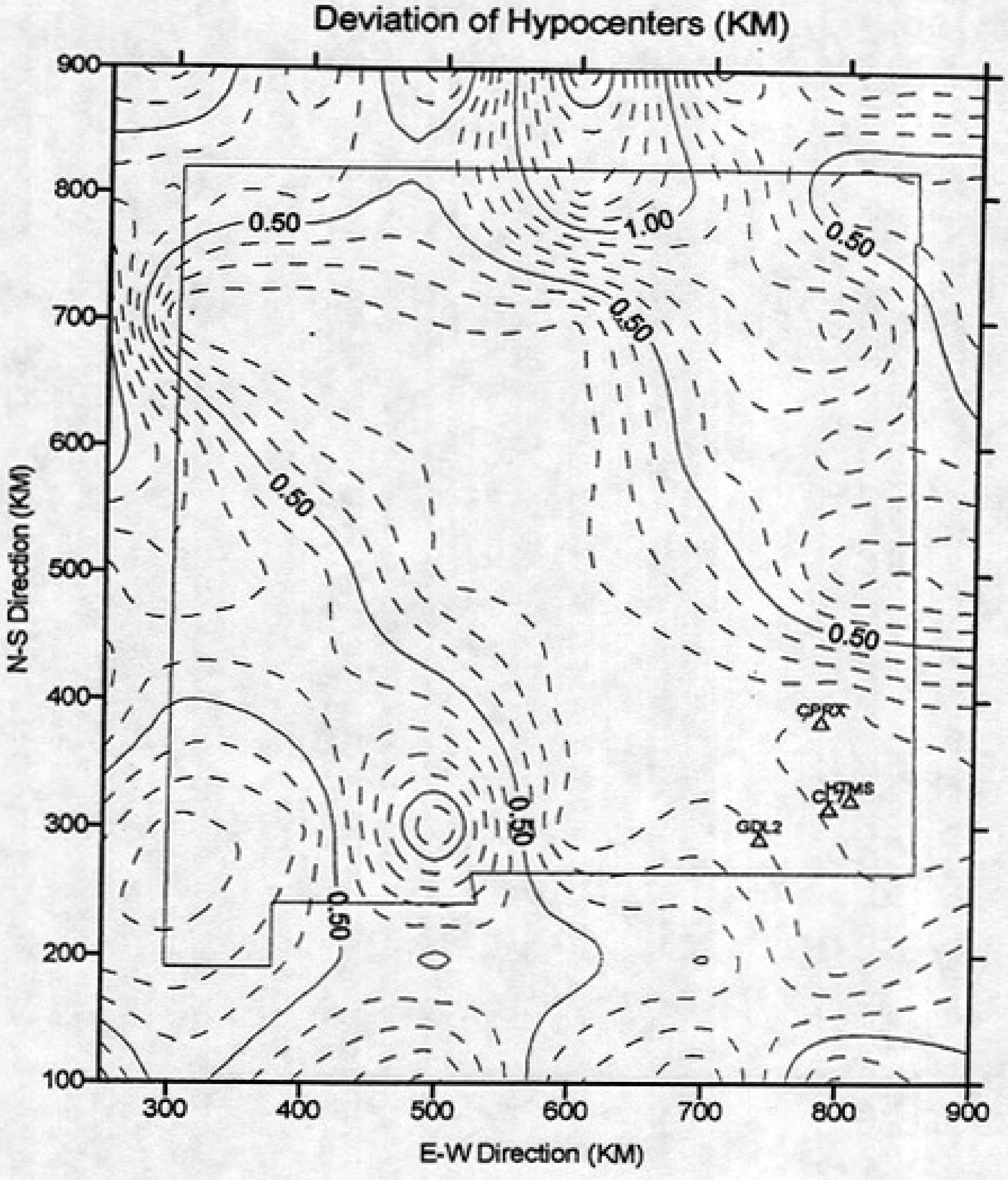

Figure 17b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. CL7, CPRX, GDL2, and HTMS of WIPP seismic network are used.

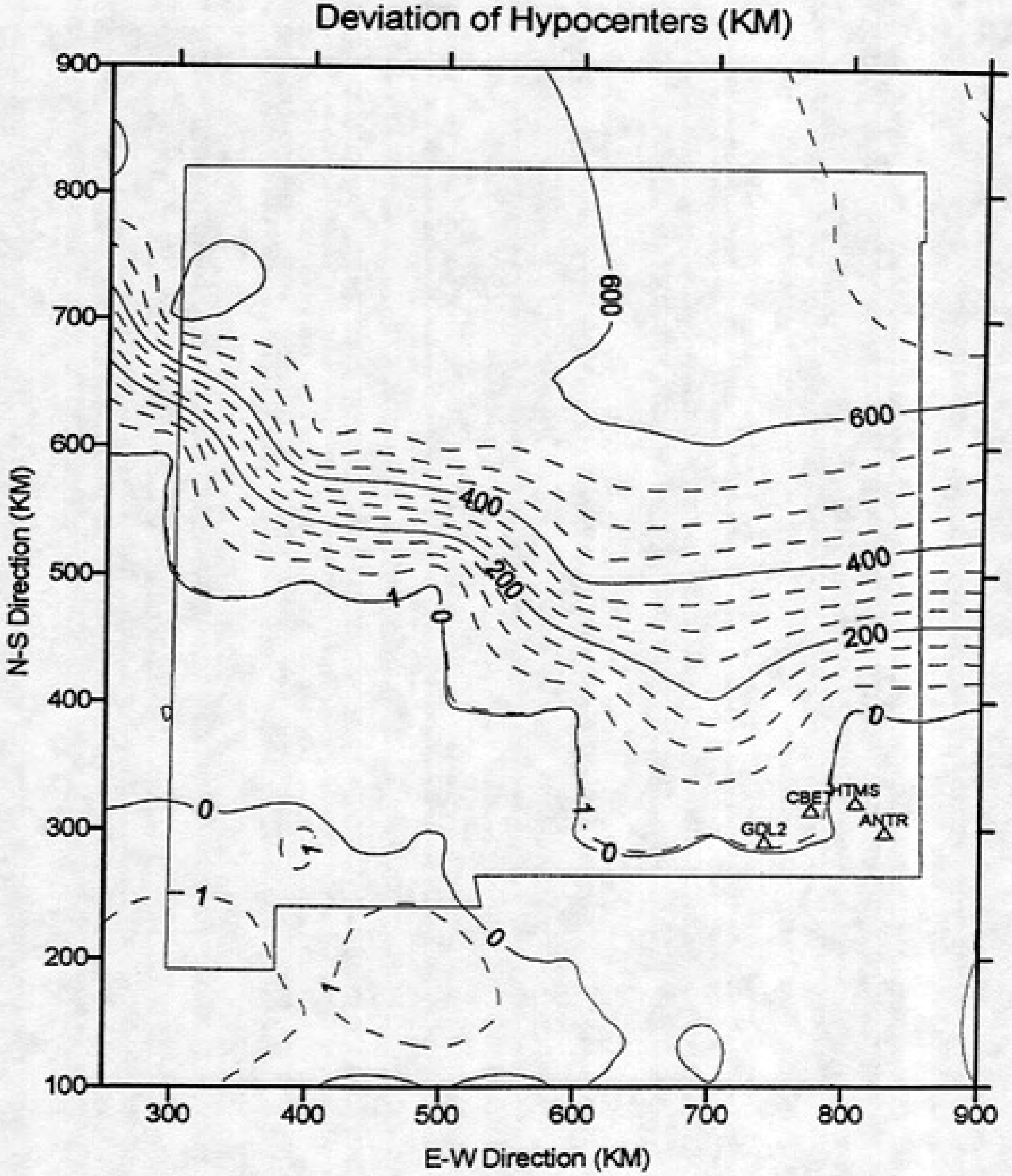

Figure 18a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. ANTR, CBET, GDL2, and HTMS of WIPP seismic network are used.

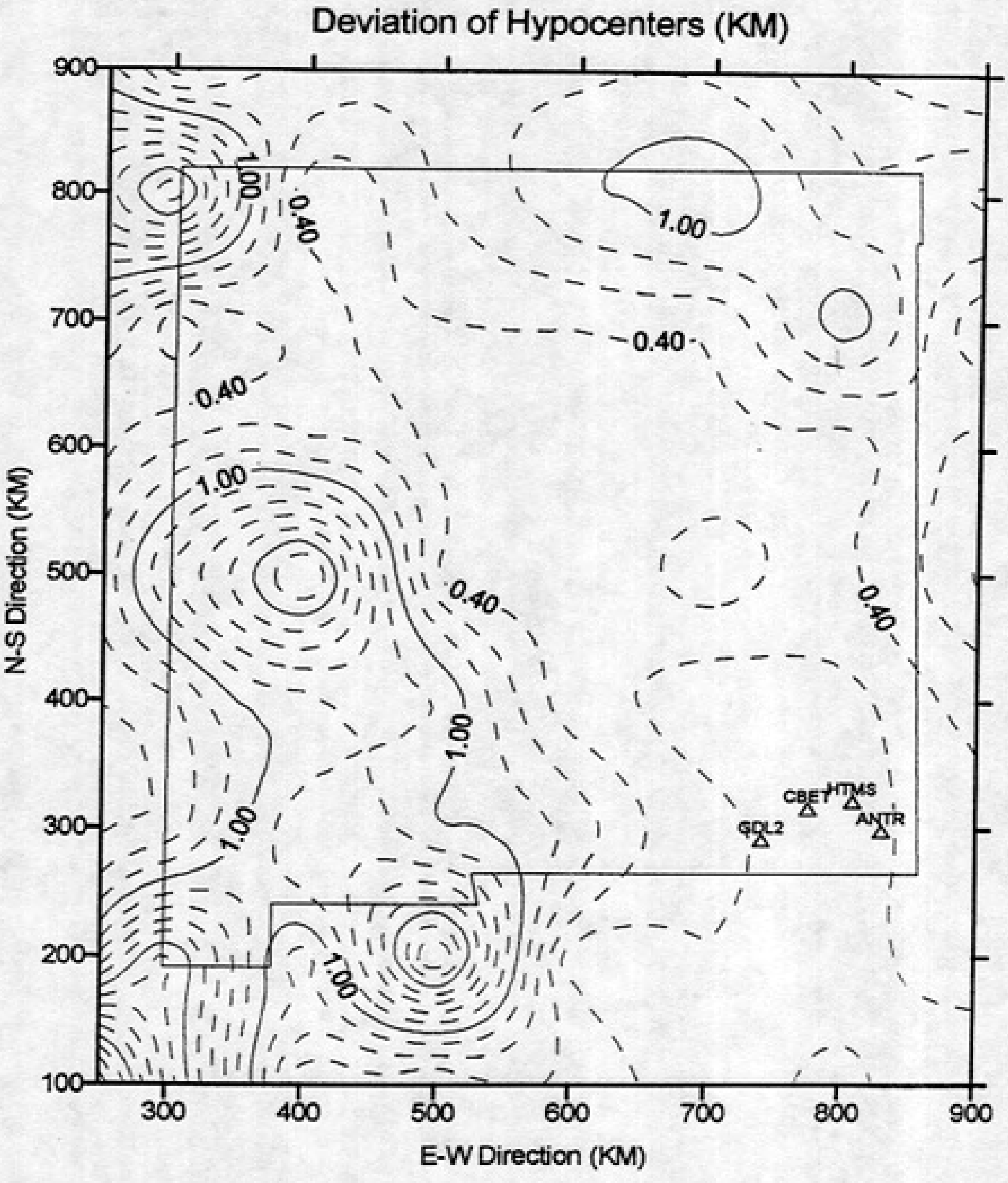

Figure 18b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. ANTR, CBET, GDL2, and HTMS of WIPP seismic network are used.

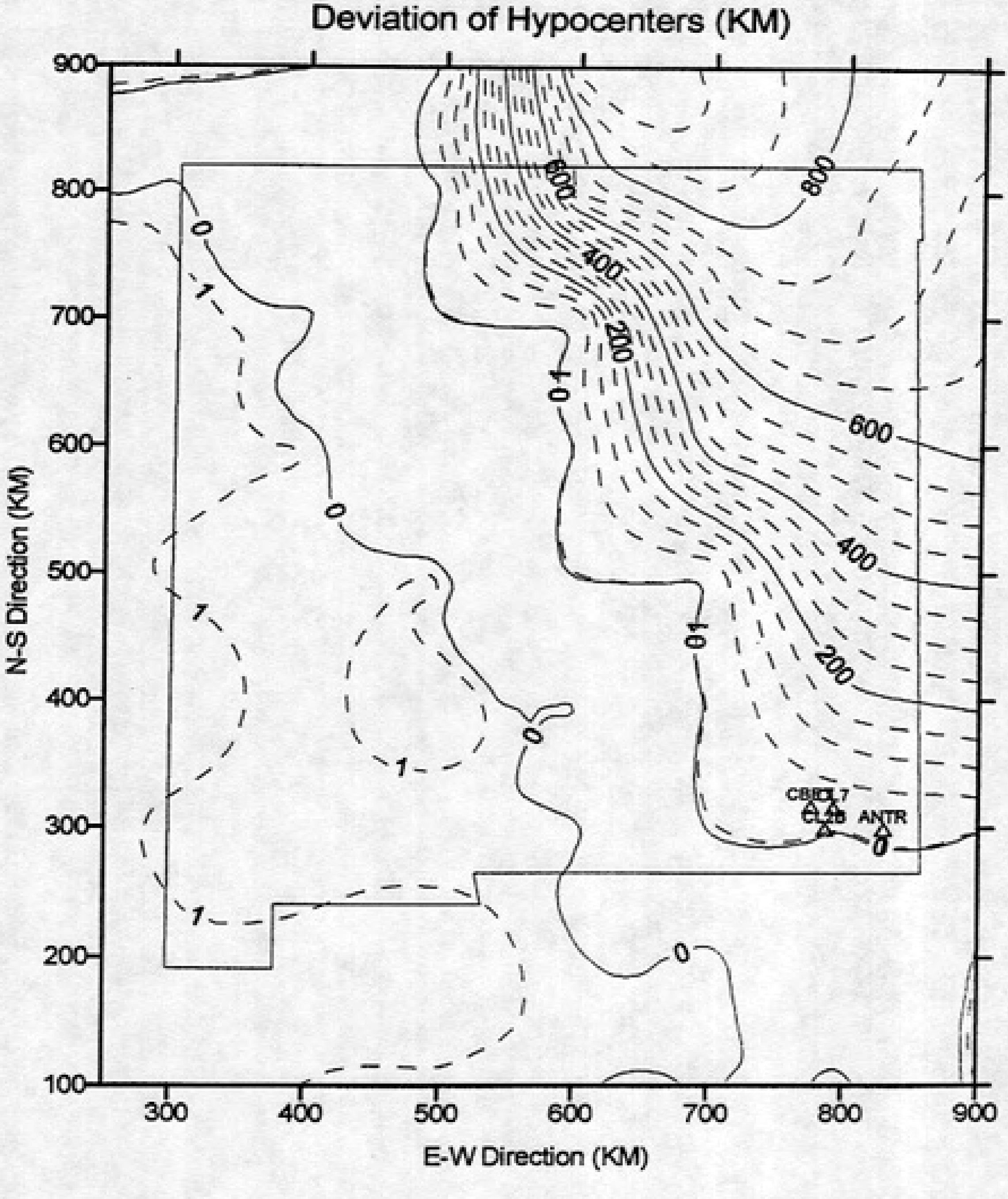

Figure 19a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. ANTR, CBET, CL2B, and CL7 of WIPP seismic network are used.

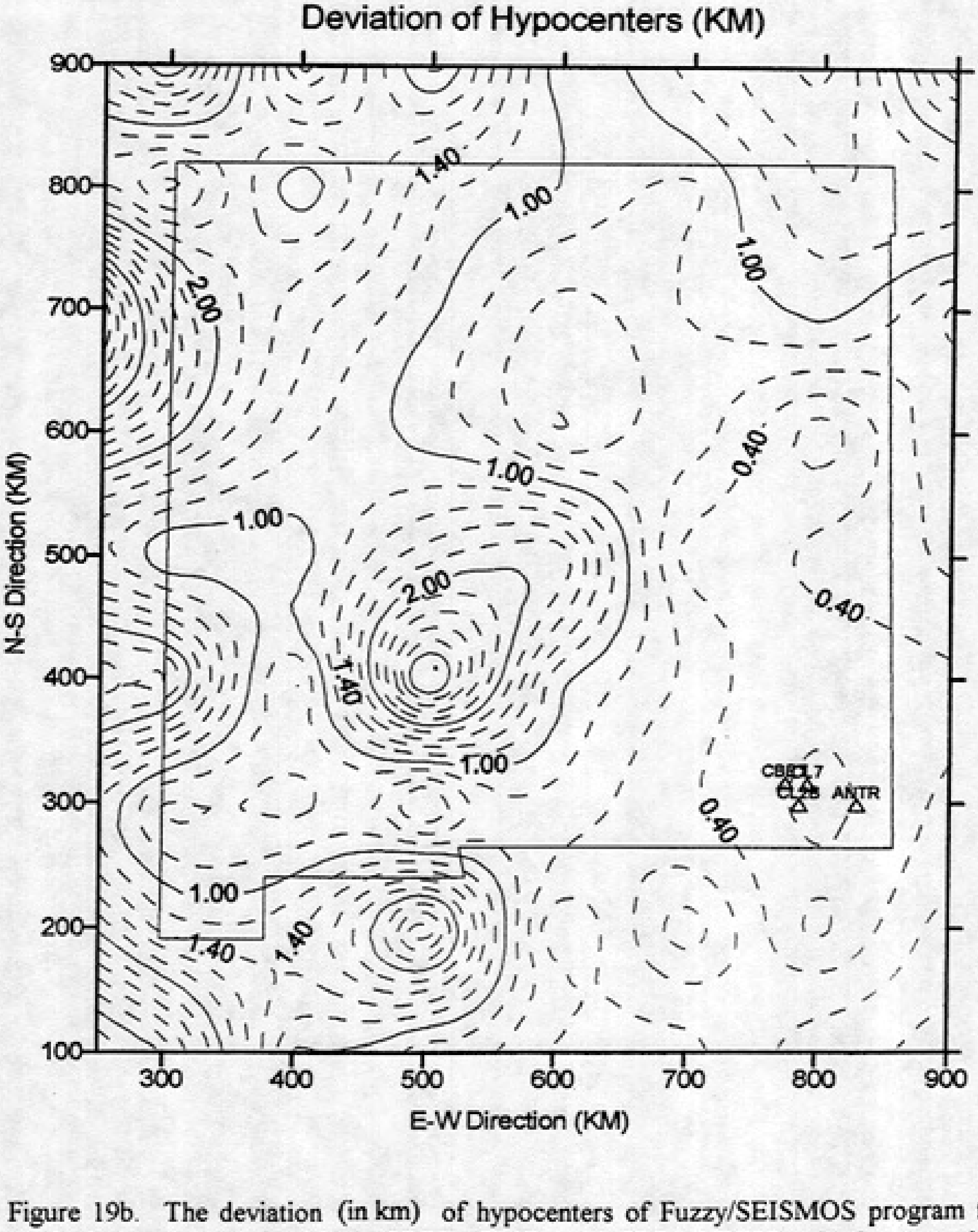

Figure 19b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. ANTR, CBET, CL2B, and CL7 of WIPP seismic network are used.

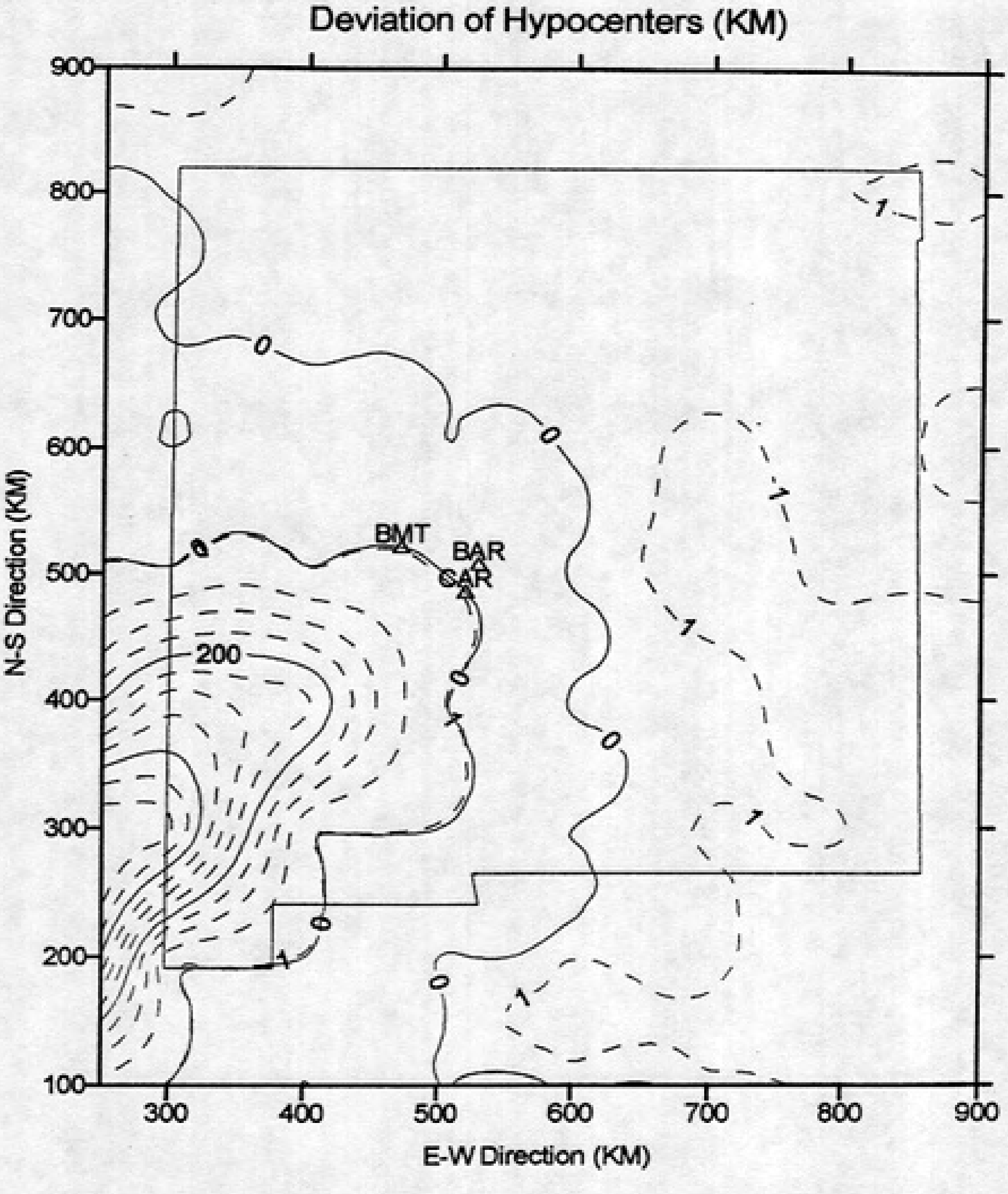

Figure 20a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. BAR, BMT, and CAR of Socorro seismic network are used.

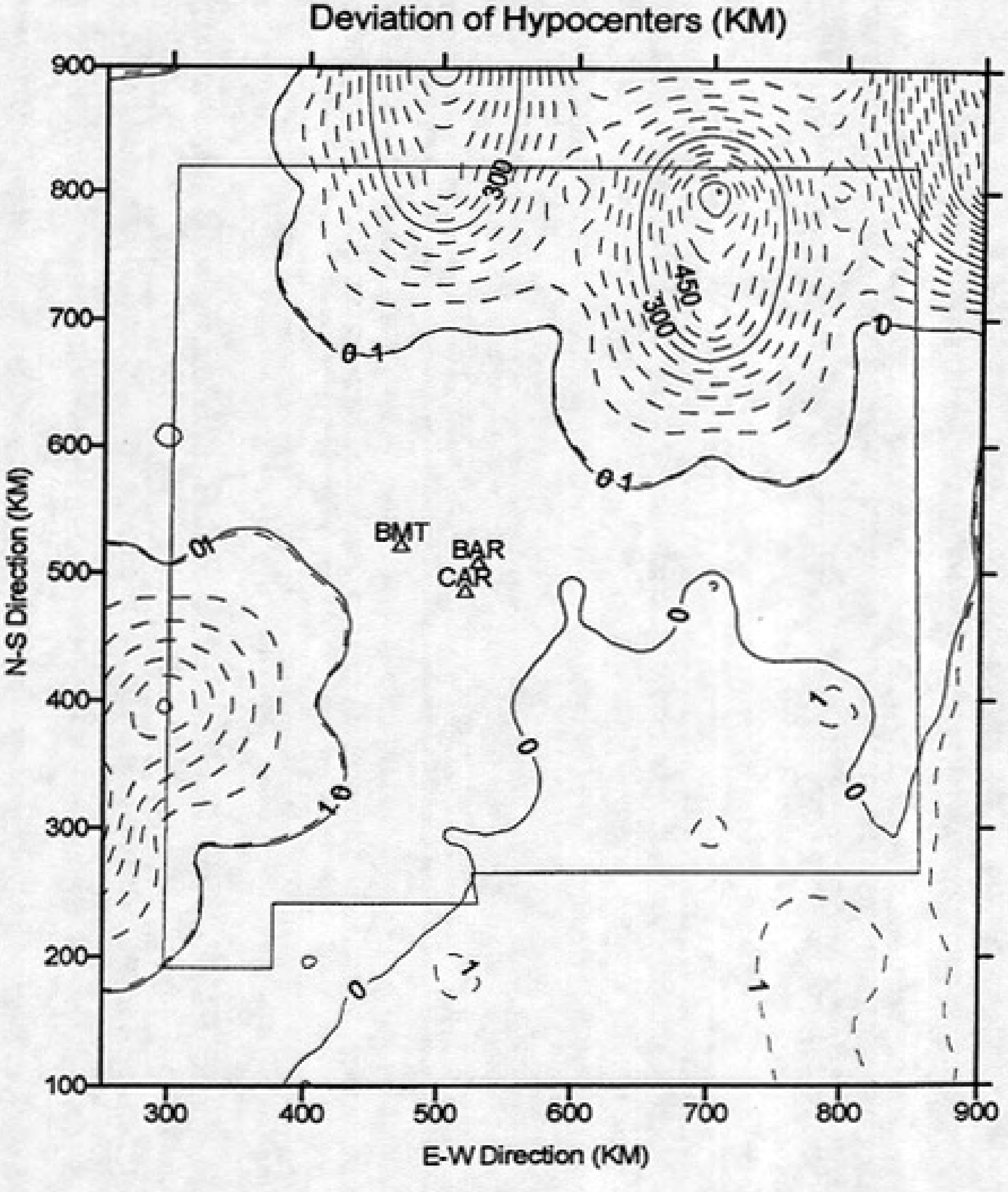

Figure 20b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. BAR, BMT, and CAR of Socorro seismic network are used.

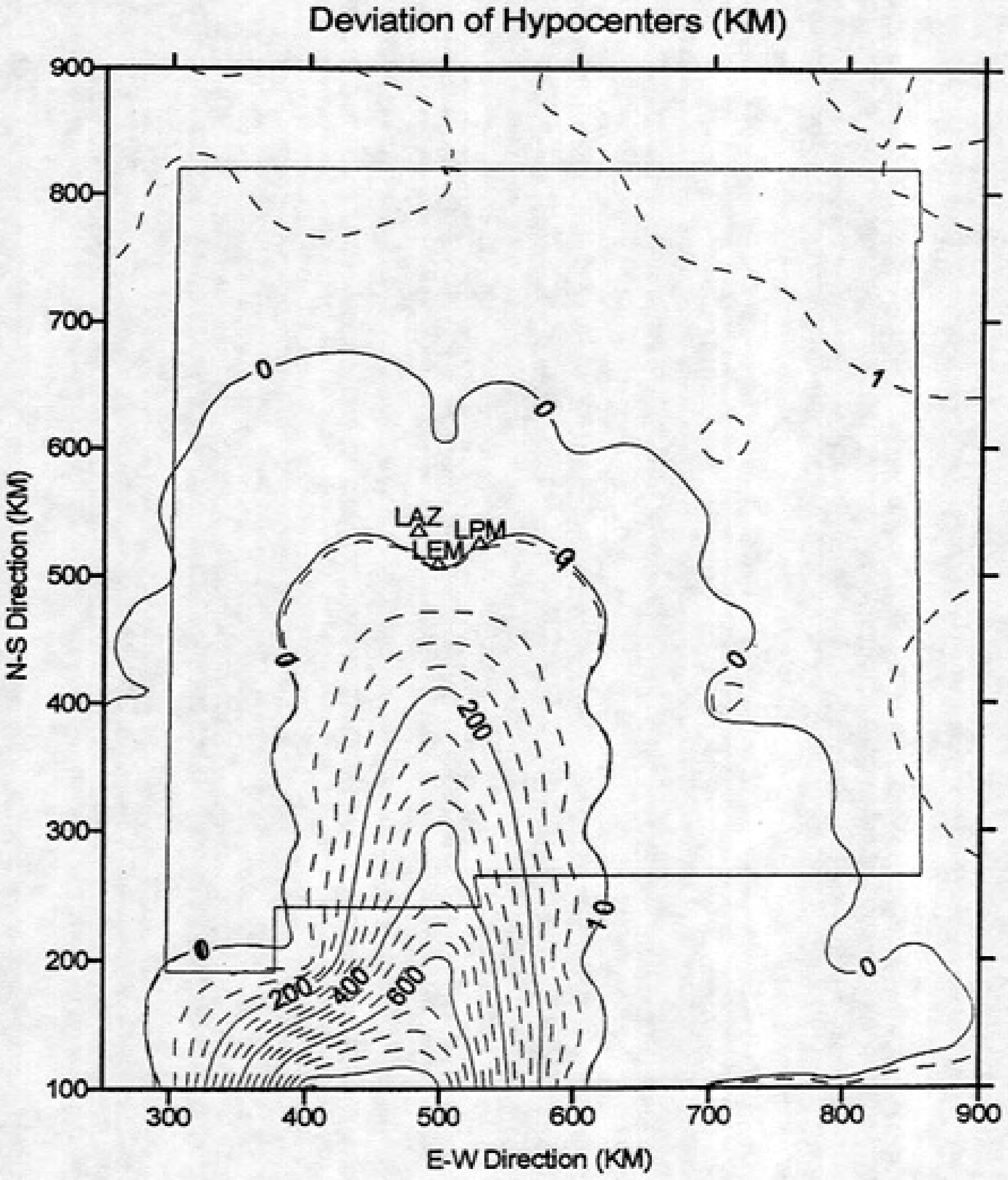

Figure 21a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. LAZ, LEM, and LPM of Socorro seismic network are used.

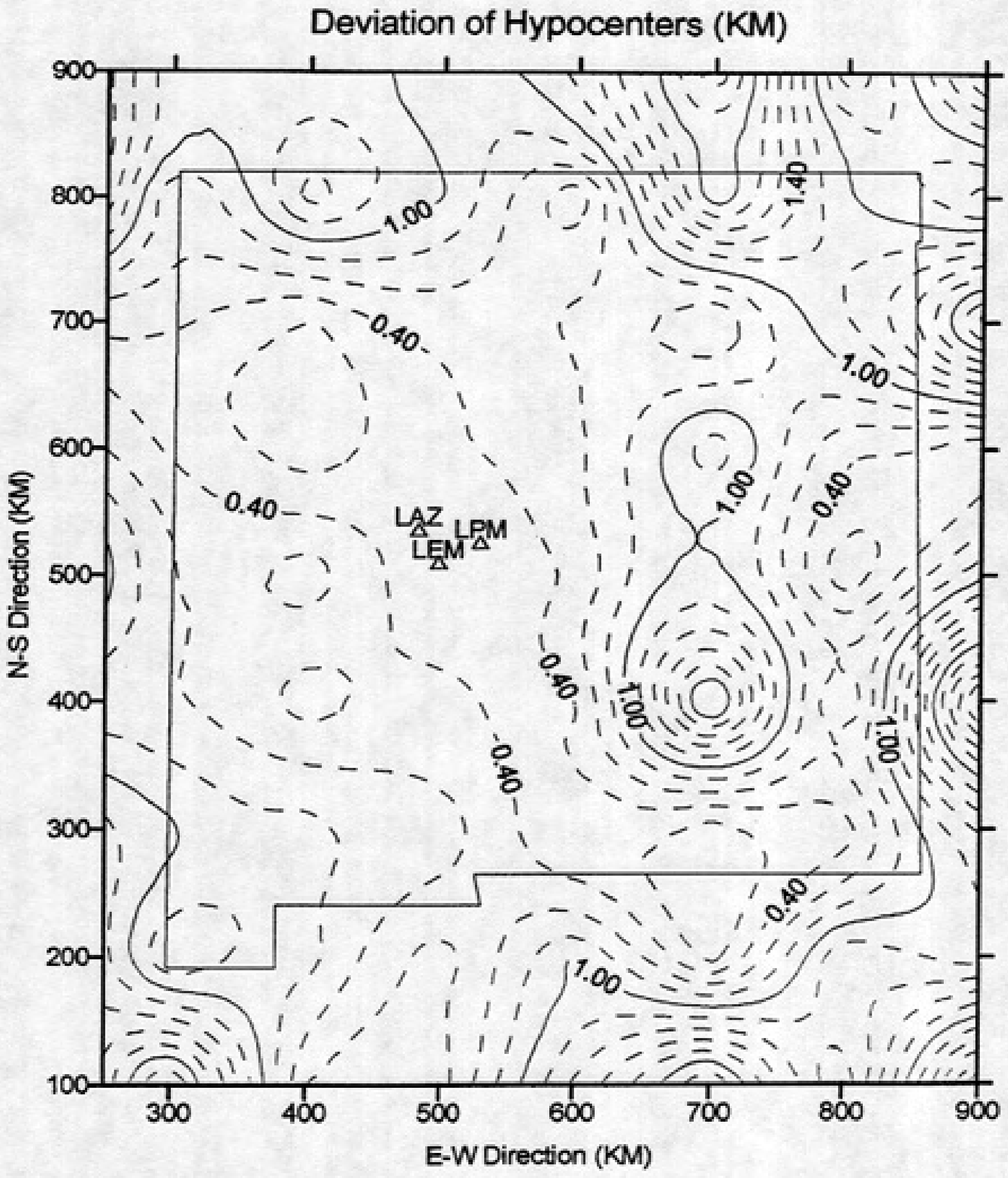

Figure 21b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. LAZ, LEM, and LPM of Socorro seismic network are used.

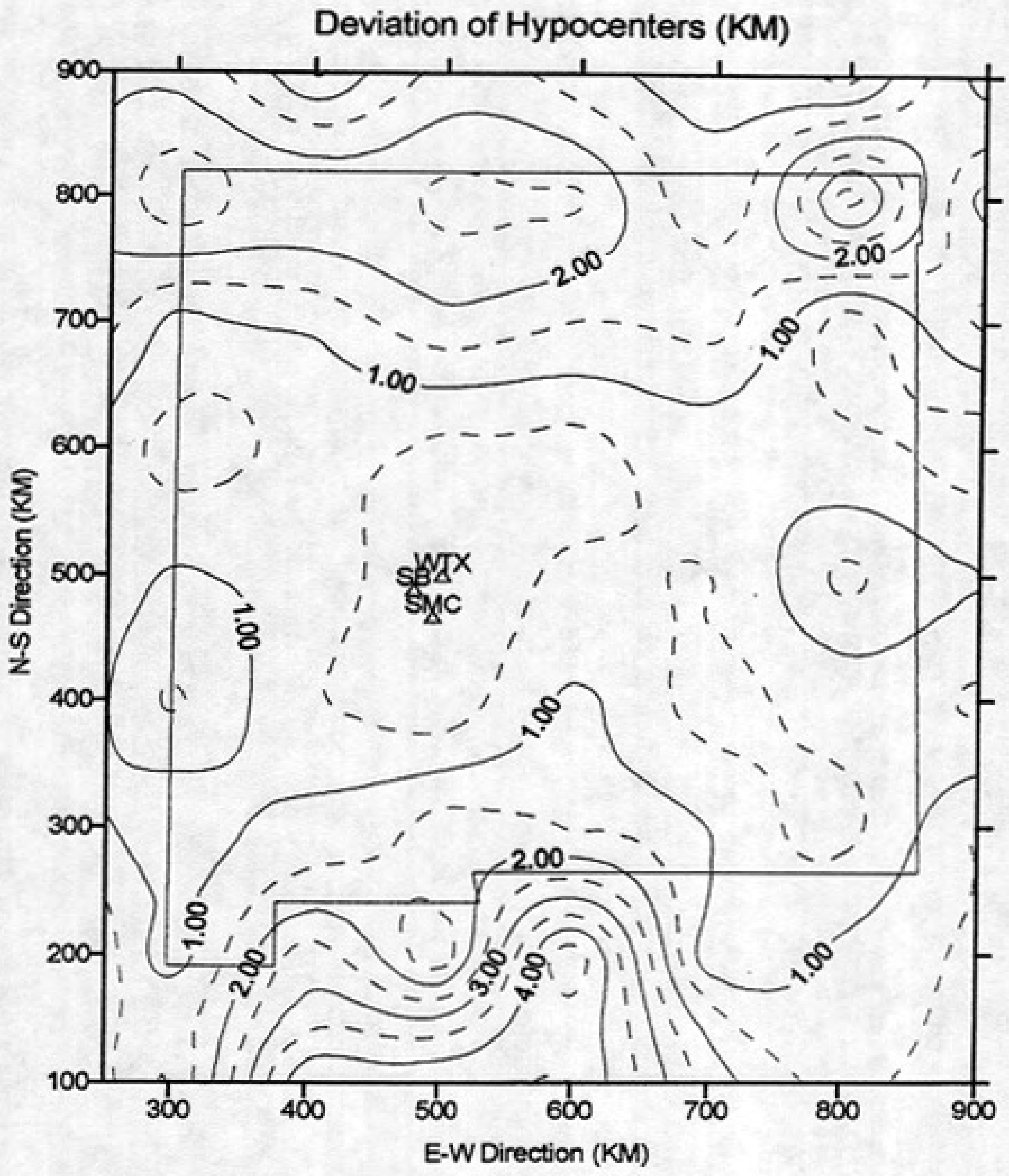

Figure 22. The deviation (in km) of hypocenters of location program from synthetic hypocenters. SB, SMC, and WTX of Socorro seismic network are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

Socorro networks tested (Figures 20 through 22), the SEISMOS program had problems with two. In the case where it was successful, the deviation of hypocenters shows up to an ~100% increase in the amount of uncertainties over four station configurations. The Fuzzy/SEISMOS program also had difficulties with one configuration (Figure 20b). Yet it was able to solve the remaining two test cases and provide reliable solutions (Figures 21b and 22). For the three station WIPP network configurations tested, both SEISMOS and Fuzzy/SEISMOS failed to produce satisfactory results (Figures 23 through 25). The figures show that the two programs have the same pattern of errors and that mislocated hypocenters may occur all over the study area and therefore epicenters based on only three stations in the WIPP network cannot be trusted.

Crustal Velocity. Two test cases were calculated with crustal velocities of 5.95 km/s and 6.35 km/s which are minus and plus 0.2 km/s with respect to the standard 6.15 km/s. The first test case with a crustal velocity of 5.95 km/s were solved by SEISMOS and Fuzzy/SEISMOS programs and had the same results (Figure 26). Surprisingly, the SEISMOS program had problems in solving earthquakes in south-west New Mexico for the second test case with crustal velocity of 6.35 km/s (Figure 27a). On the other had, the Fuzzy/SEISMOS program produced satisfactory results. As expected the errors are approximately concentric about the network and reach substantial levels at distances of ~200 km for all solved cases (Figures 26 and 27b). Figures 26 and 27b illustrate the need to have a half-space velocity which is the best average for the entire study area.

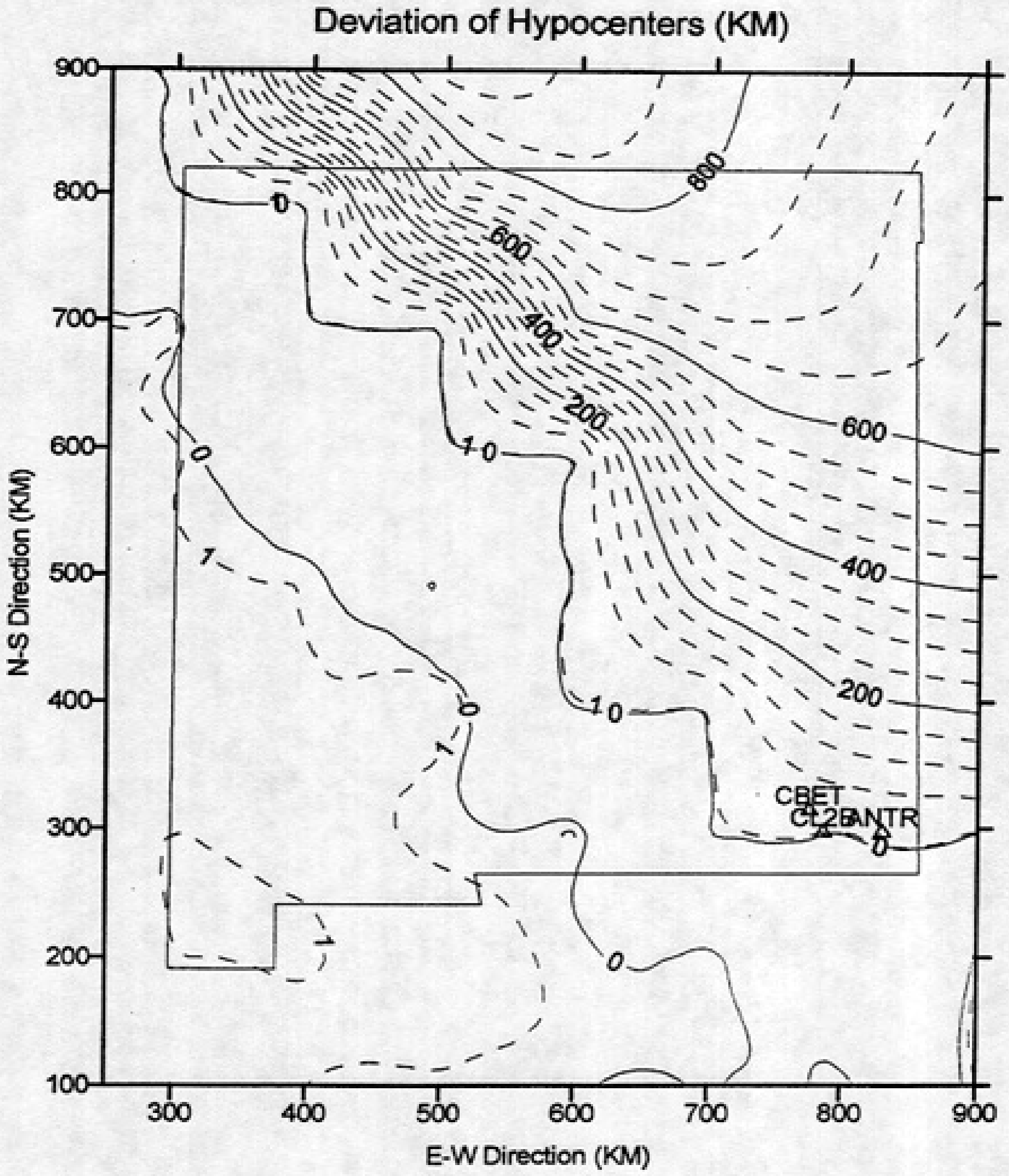

Figure 23a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. ANTR, CBET, and CL2B of WIPP seismic network are used.

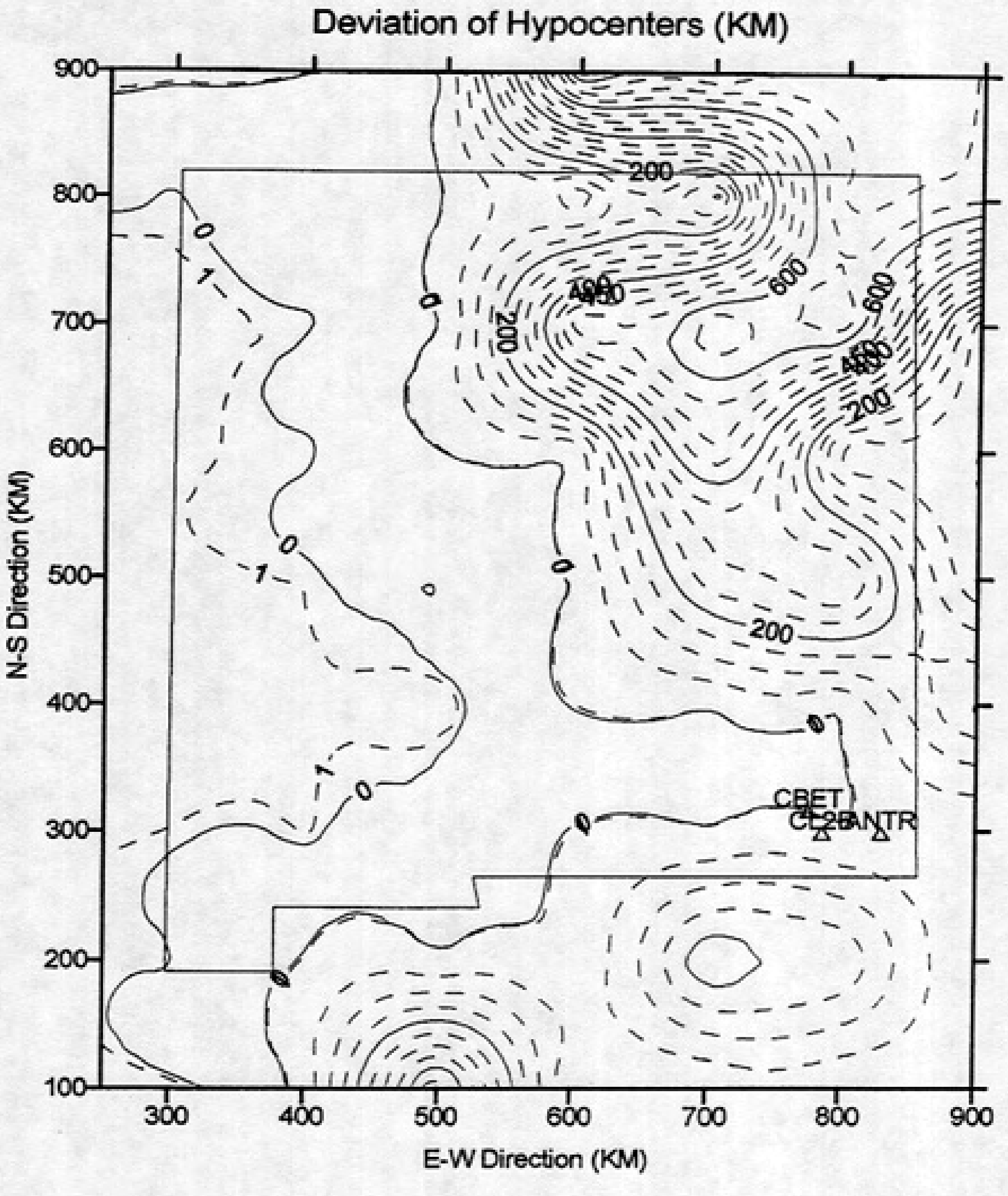

Figure 23b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. ANTR, CBET, and CL2B of WIPP seismic network are used.

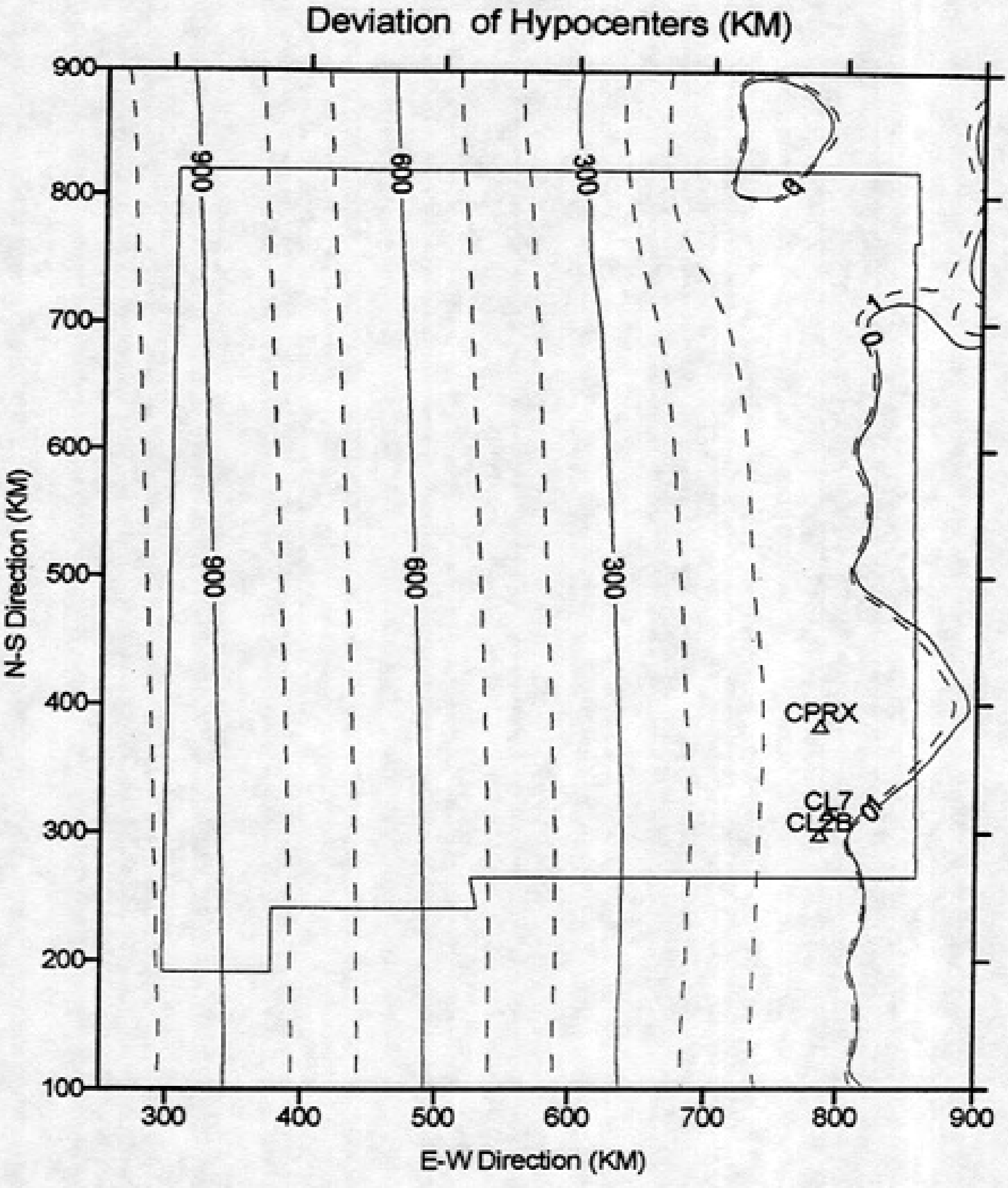

Figure 24a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. CL2B, CL7, and CPRX of WIPP seismic network are used.

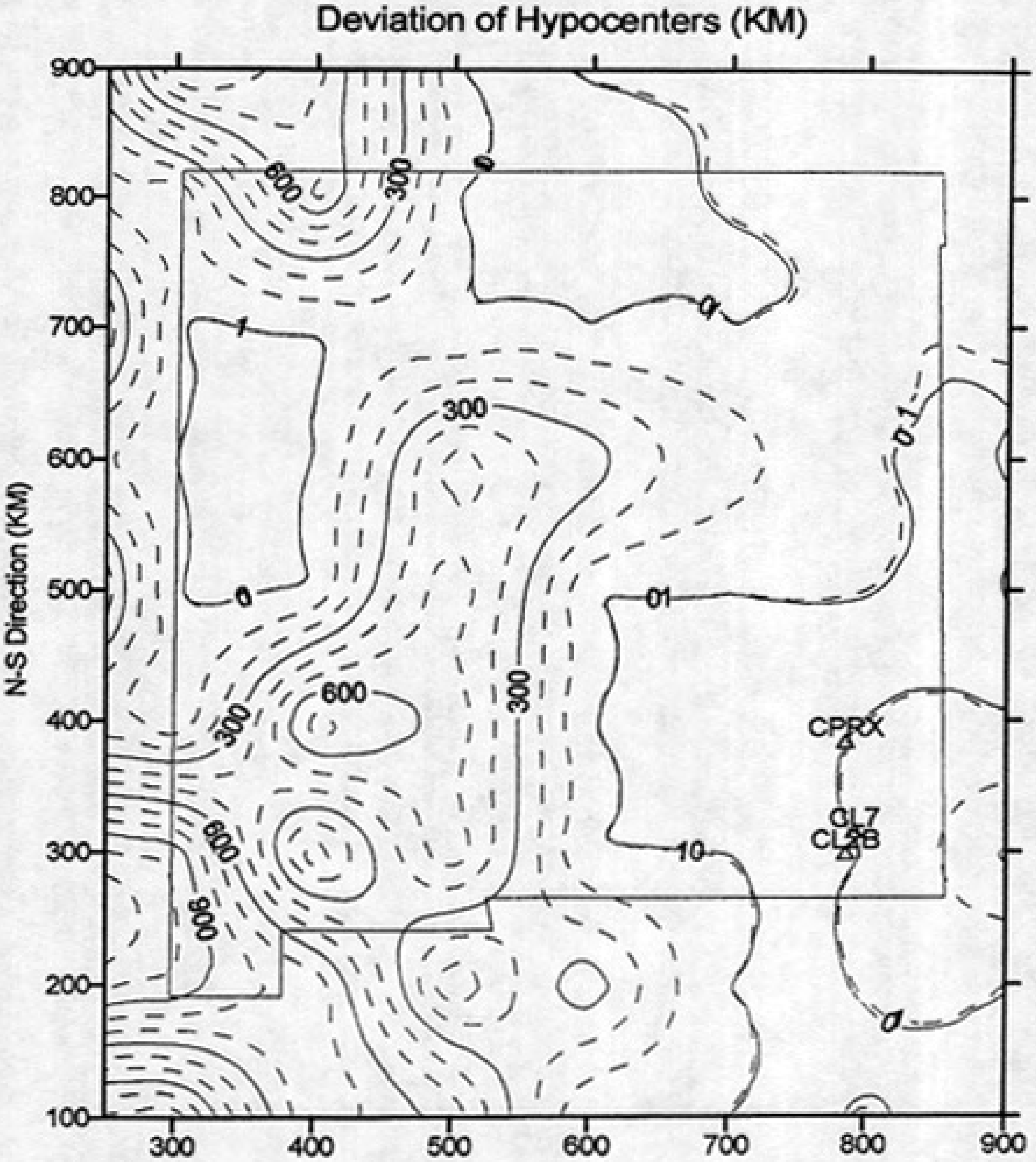

Figure 24b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. CL2B, CL7, and CPRX of WIPP seismic network are used.

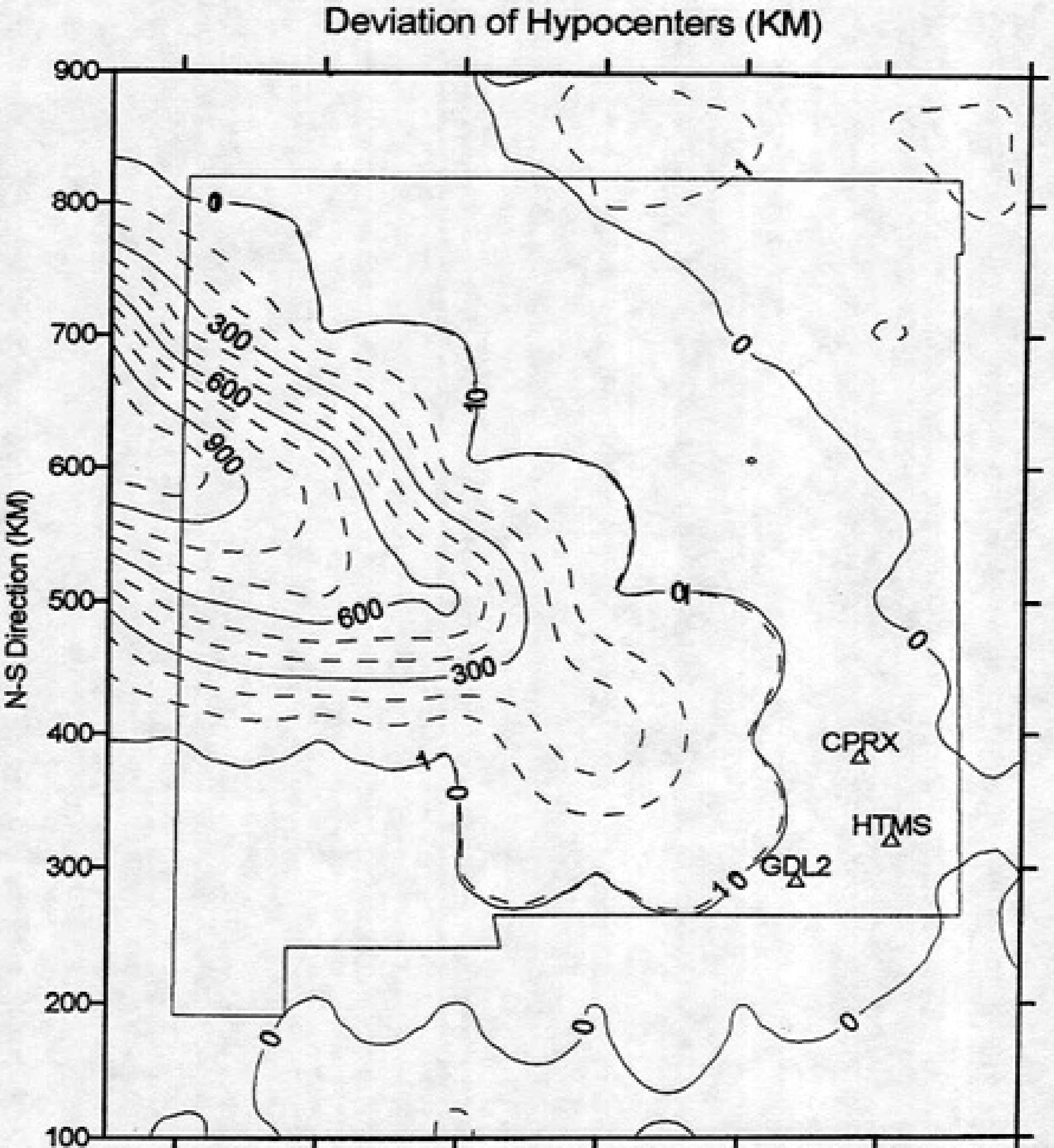

Figure 25a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. CPRX, GDL2, and HTMS of WIPP seismic network are used.

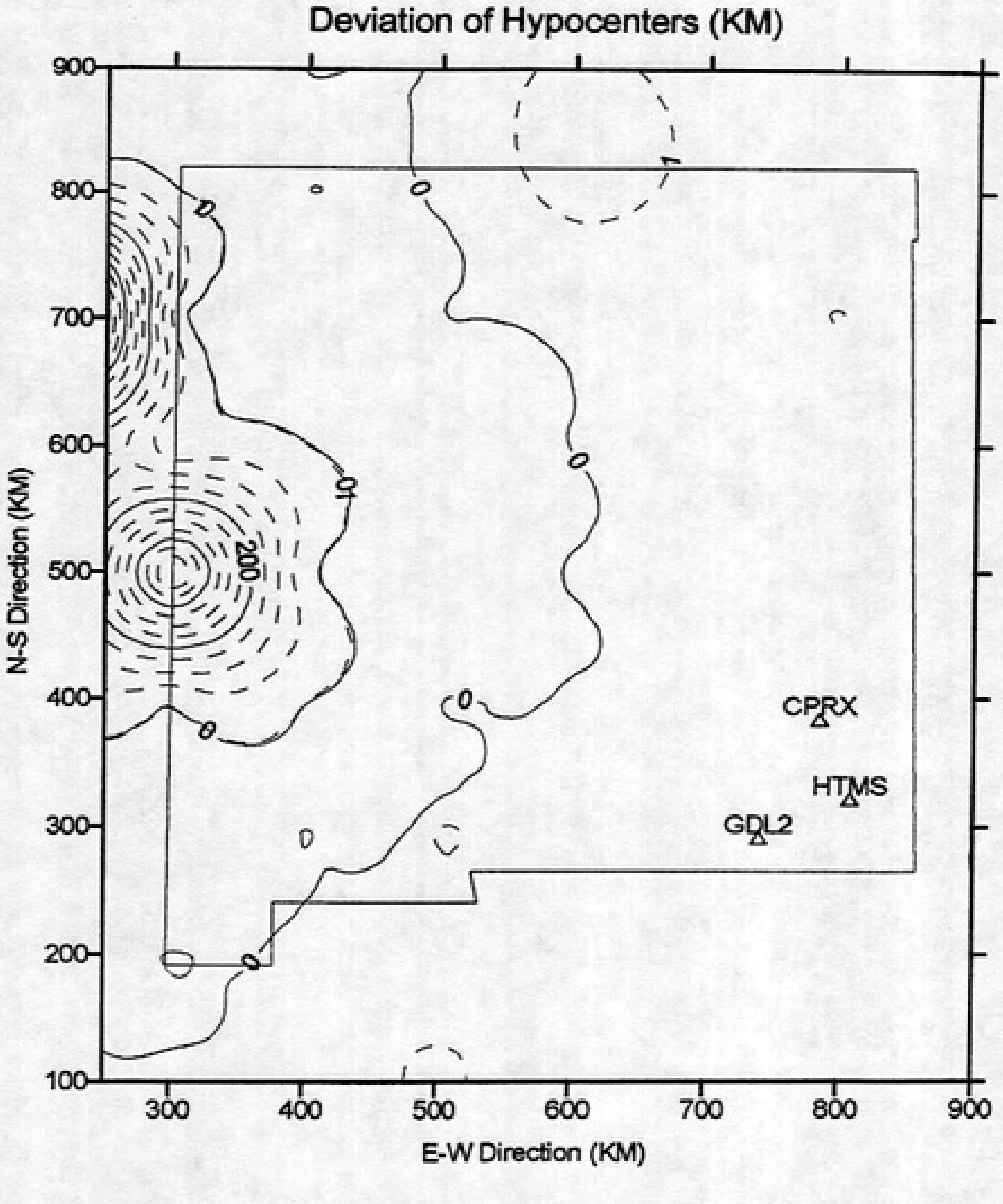

Figure 25b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. CPRX, GDL2, and HTMS of WIPP seismic network are used.

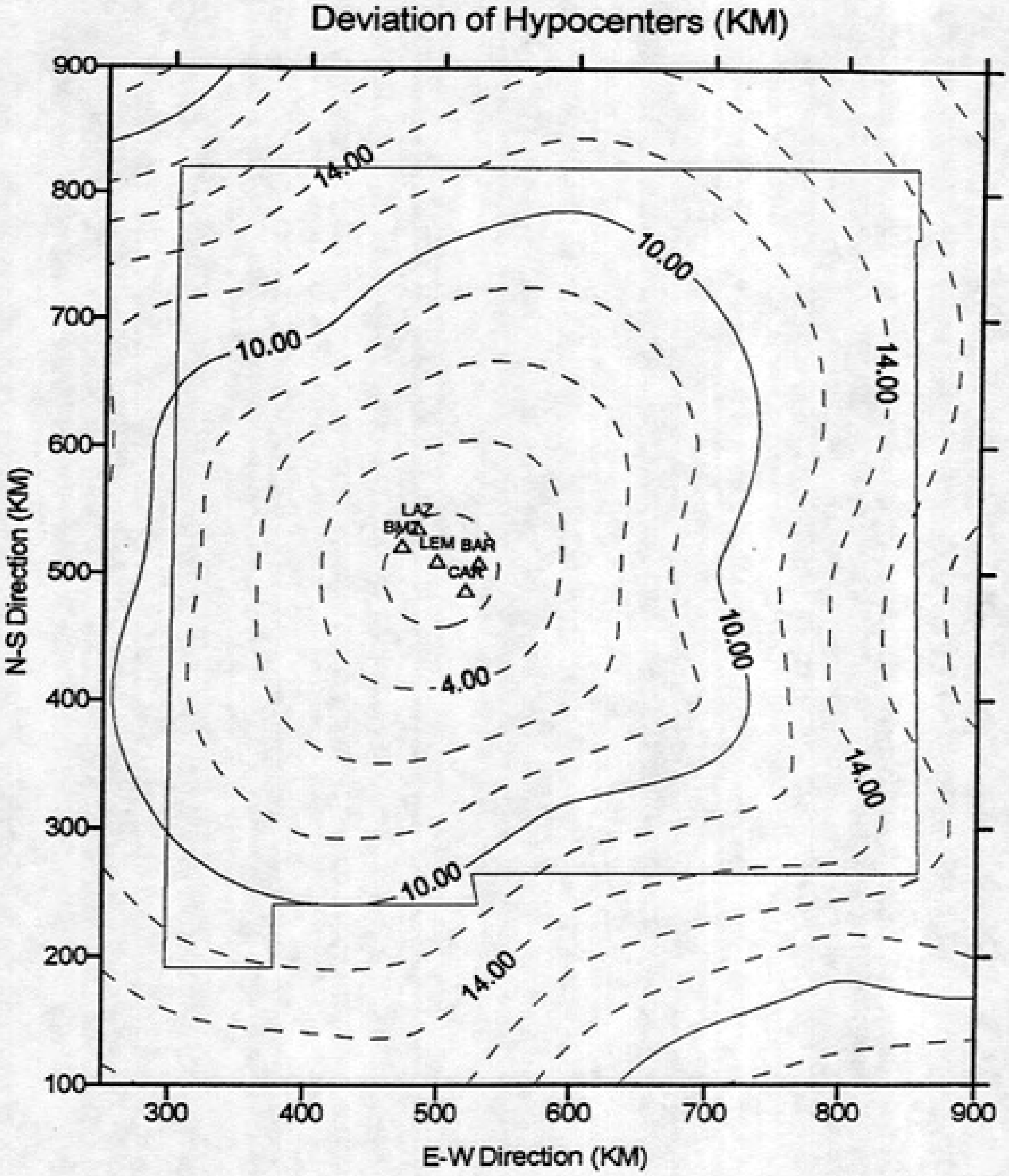

Figure 26. The deviation (in km) of hypocenters of location program from synthetic hypocenters. The crustal velocity is 5.95 km/s. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

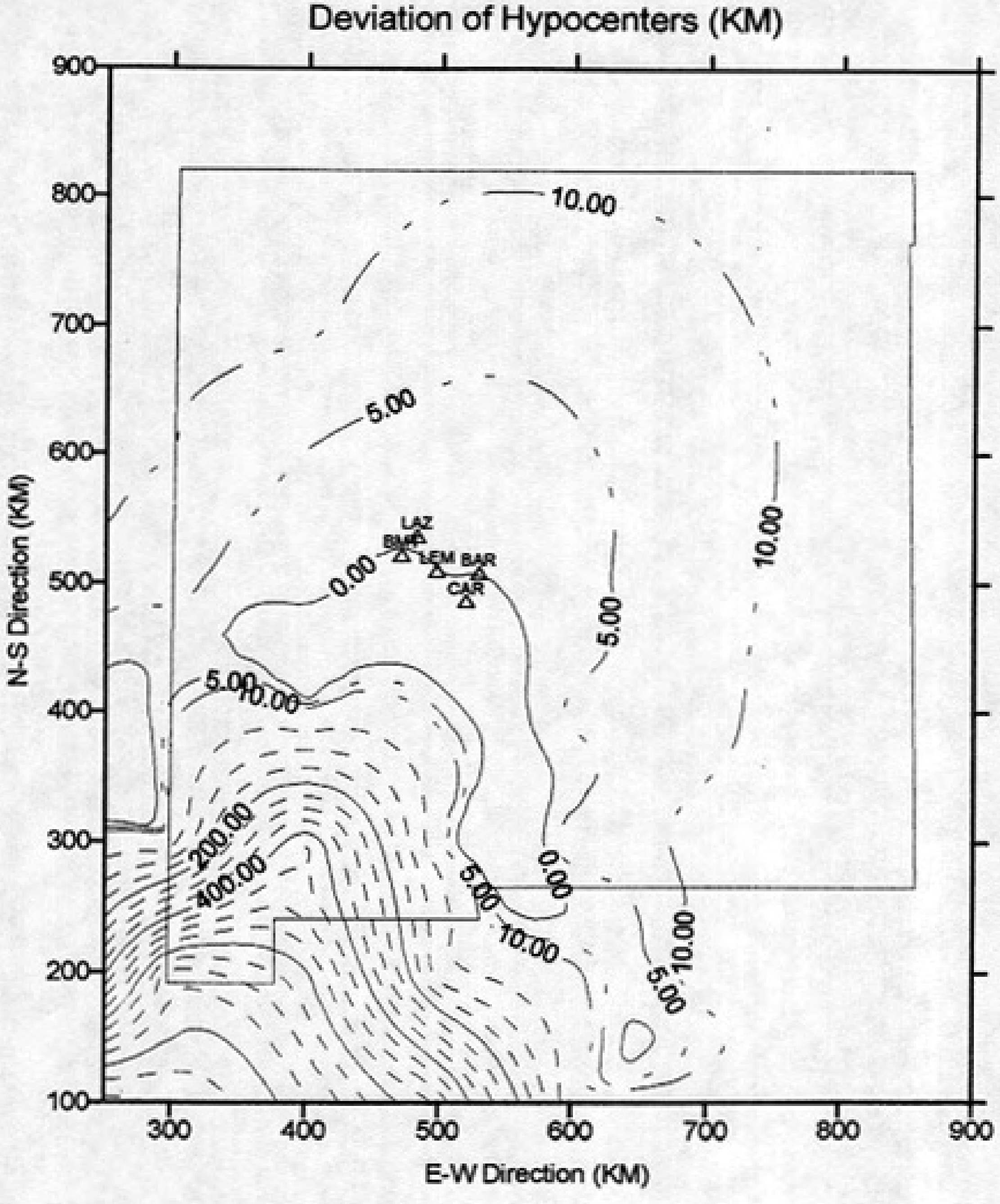

Figure 27a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. The crustal velocity is 6.35 km/s. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used.

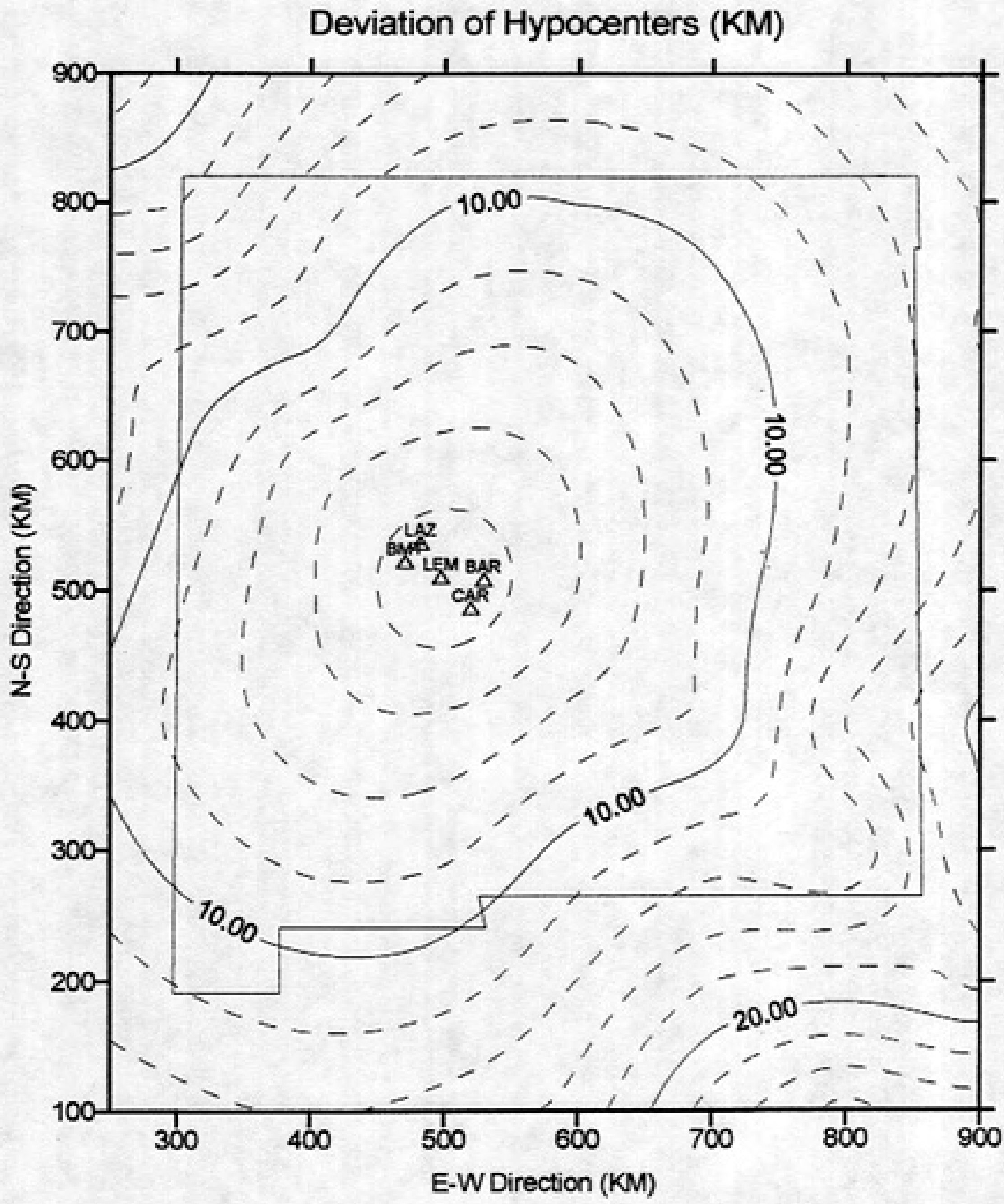

Figure 27b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. The crustal velocity is 6.35 km/s. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used.

Poisson's Ratio. Two test cases were calculated with Poisson's ratios of 0.24 and 0.26 which are minus and plus 0.01 with respect to the standard value of 0.25. The SEISMOS program failed to solve the test case with Poisson's ratio of 0.24 (Figure 28a) and the Fuzzy/SEISMOS program was successful (Figure 28b). Yet for the test case with Poisson's ratio of 0.26, both SEISMOS and Fuzzy/SEISMOS programs produce the same results (Figure 29). The seismic station configuration is the same as the crustal velocity case and the deviation plots have the same shape, even for poorly behaved results. For both well resolved cases (Figures 28b and 29) the errors become large at distances of 200~300 km and illustrate the need to have the best average Poisson's ratio for the entire study area.

Background Noise. The effects of adding ±0.5 seconds random noise to the perfect arrival time data are shown in Figures 30a through 30e. The seismic station configuration remains unchanged from the previous velocity and Poisson's ratio tests. The common feature of these five random noise tests is that deviations are about the same magnitude. However the spatial configuration of hypocenter differences changes with each distribution of random noise although there remain some similarities.

Real Earthquake Data. Figure 31a shows the obtained hypocenter for an earthquake on September 5, 1993 using data from 5 Socorro network stations and 6 WIPP network stations. This hypocenter is termed the standard. Using WIPP network stations only, both location programs produce a hypocentral location close to standard location.

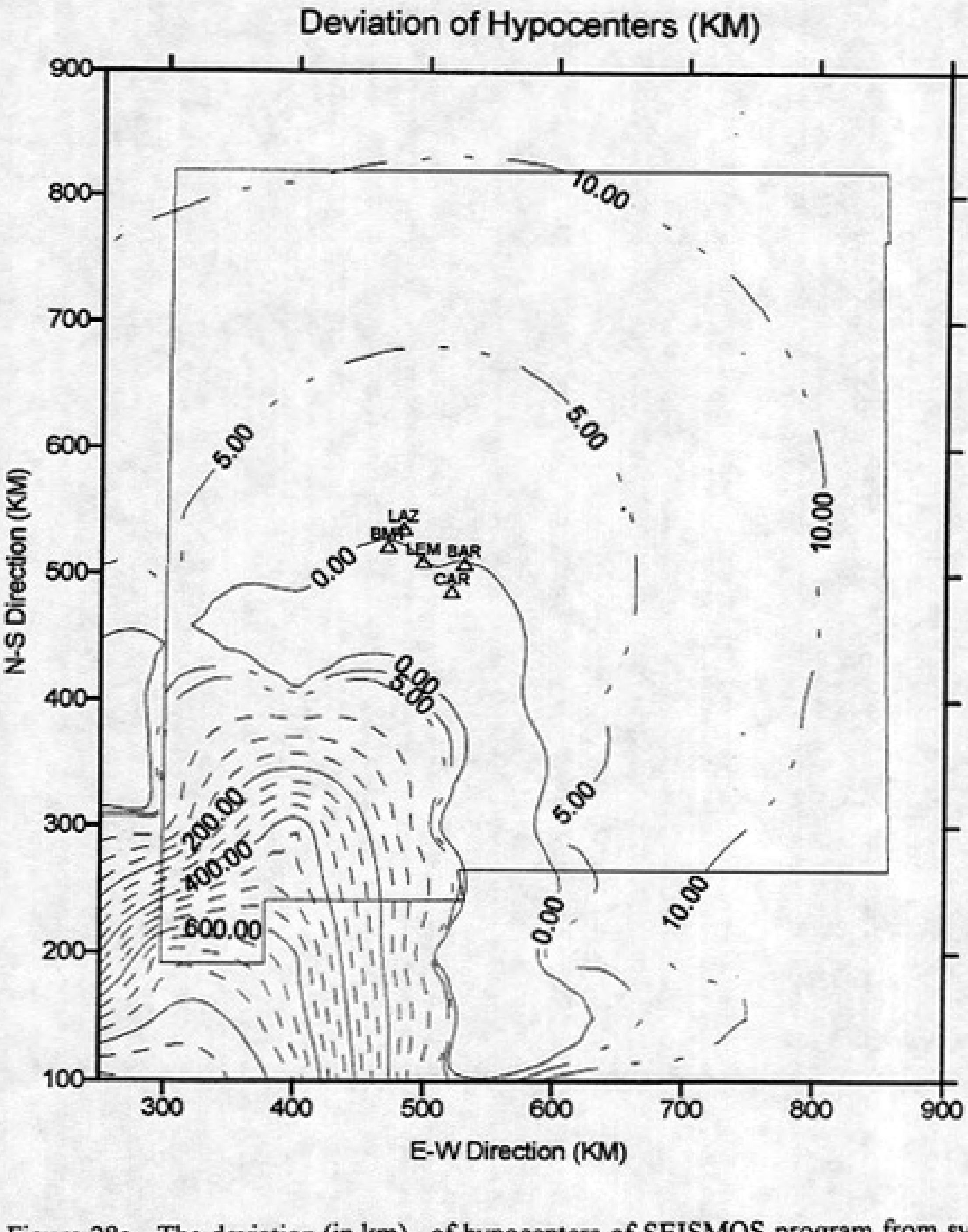

Figure 28a. The deviation (in km) of hypocenters of SEISMOS program from synthetic hypocenters. Poisson's ratio is 0.24. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used.

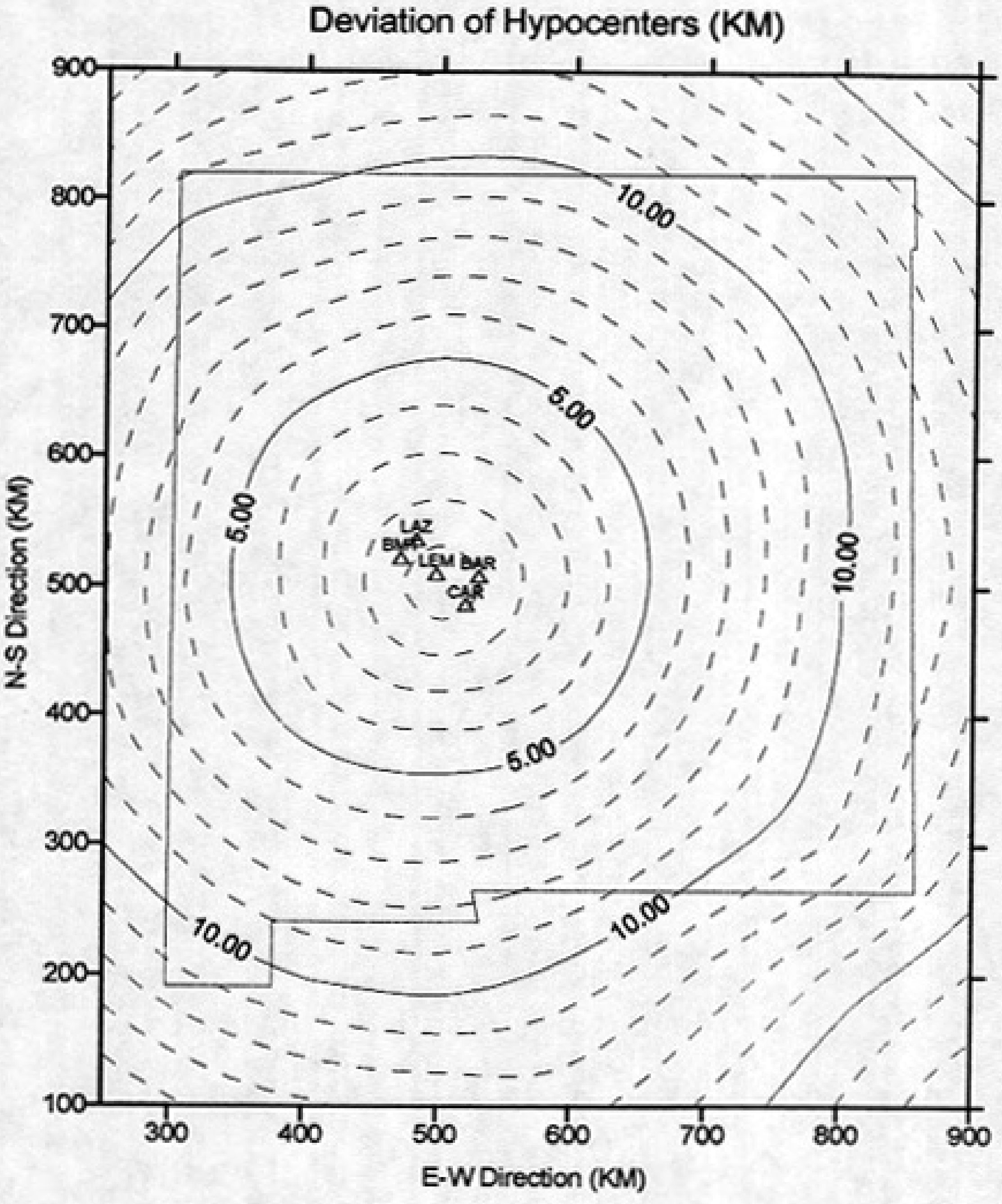

Figure 28b. The deviation (in km) of hypocenters of Fuzzy/SEISMOS program from synthetic hypocenters. Poisson's ratio is 0.24. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used.

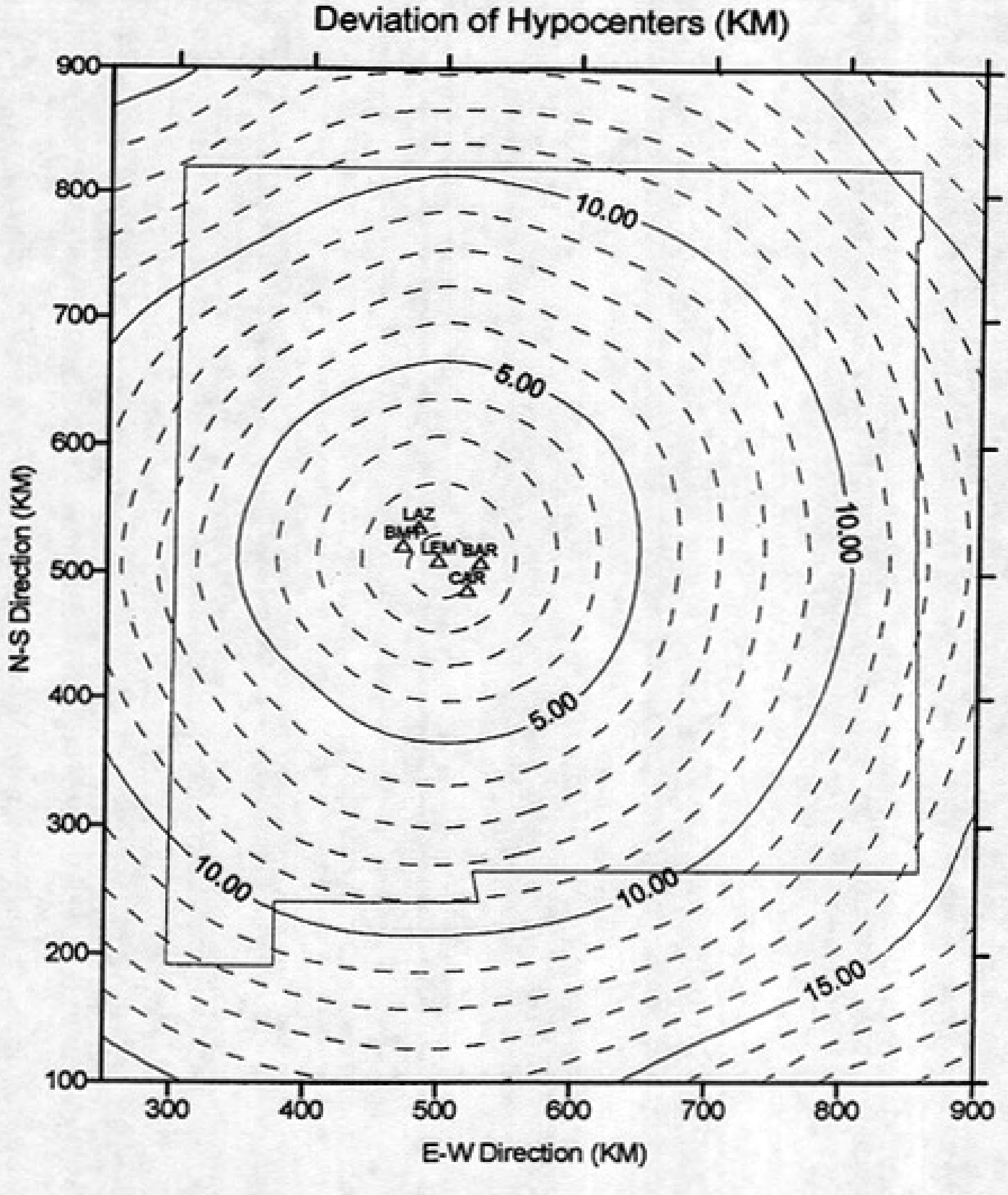

Figure 29. The deviation (in km) of hypocenters of location program from synthetic hypocenters. Poisson's ratio is 0.26. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

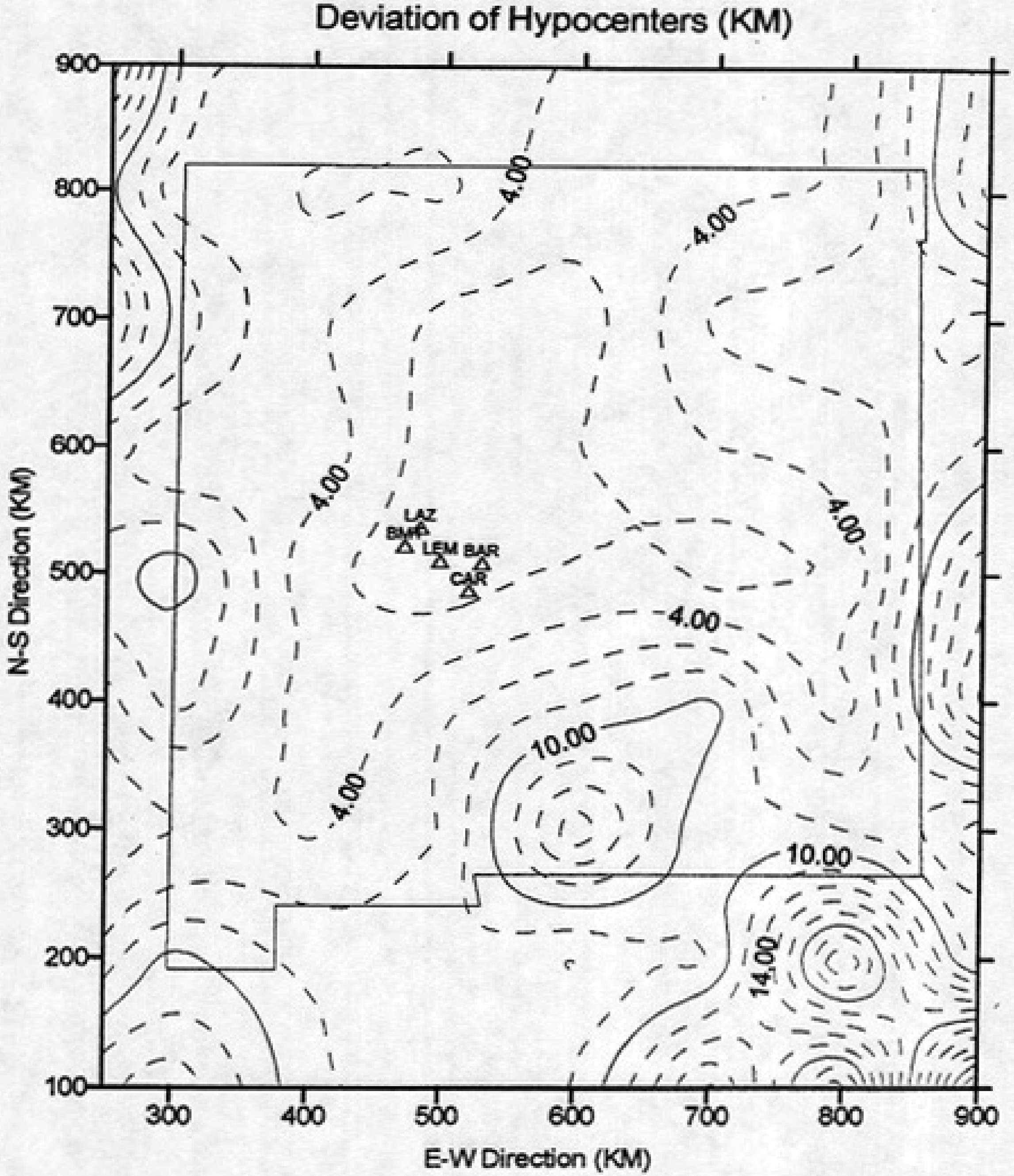

Figure 30a. The deviation (in km) of hypocenters of location program from synthetic hypocenters. The random background noise is ±0.5 seconds. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

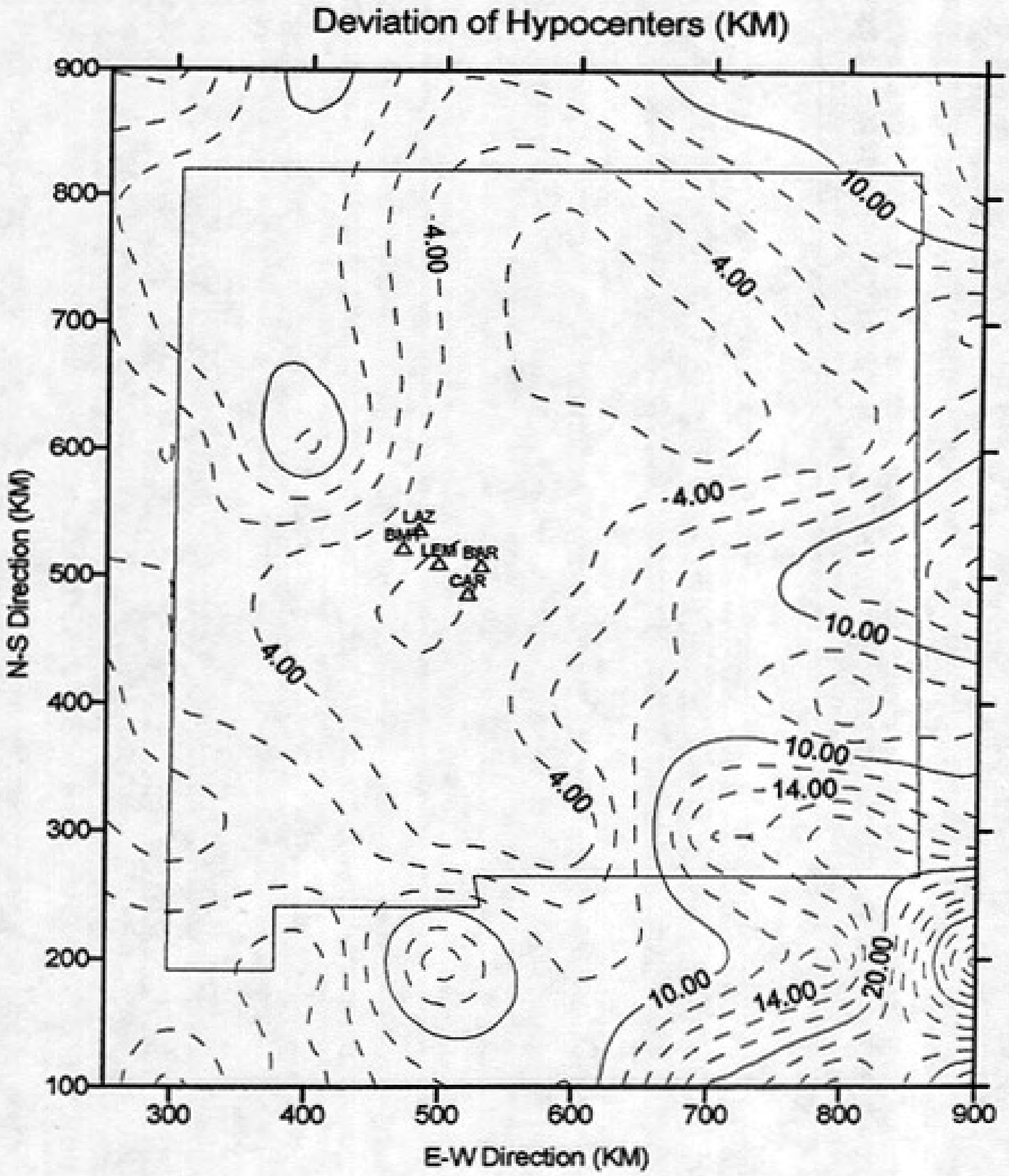

Figure 30b. The deviation (in km) of hypocenters of location program from synthetic hypocenters. The random background noise is ±0.5 seconds. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

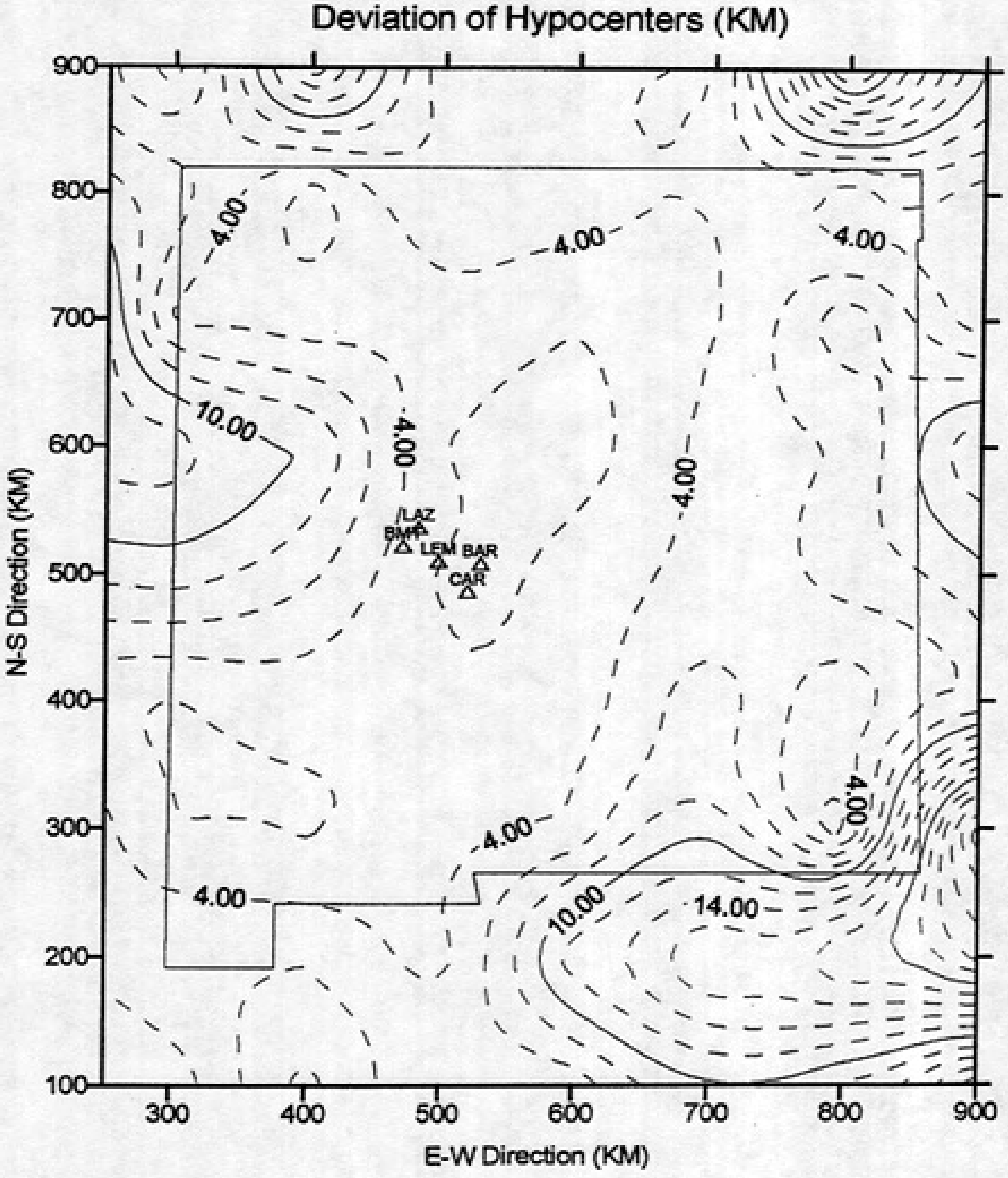

Figure 30c. The deviation (in km) of hypocenters of location program from synthetic hypocenters. The random background noise is ±0.5 seconds. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

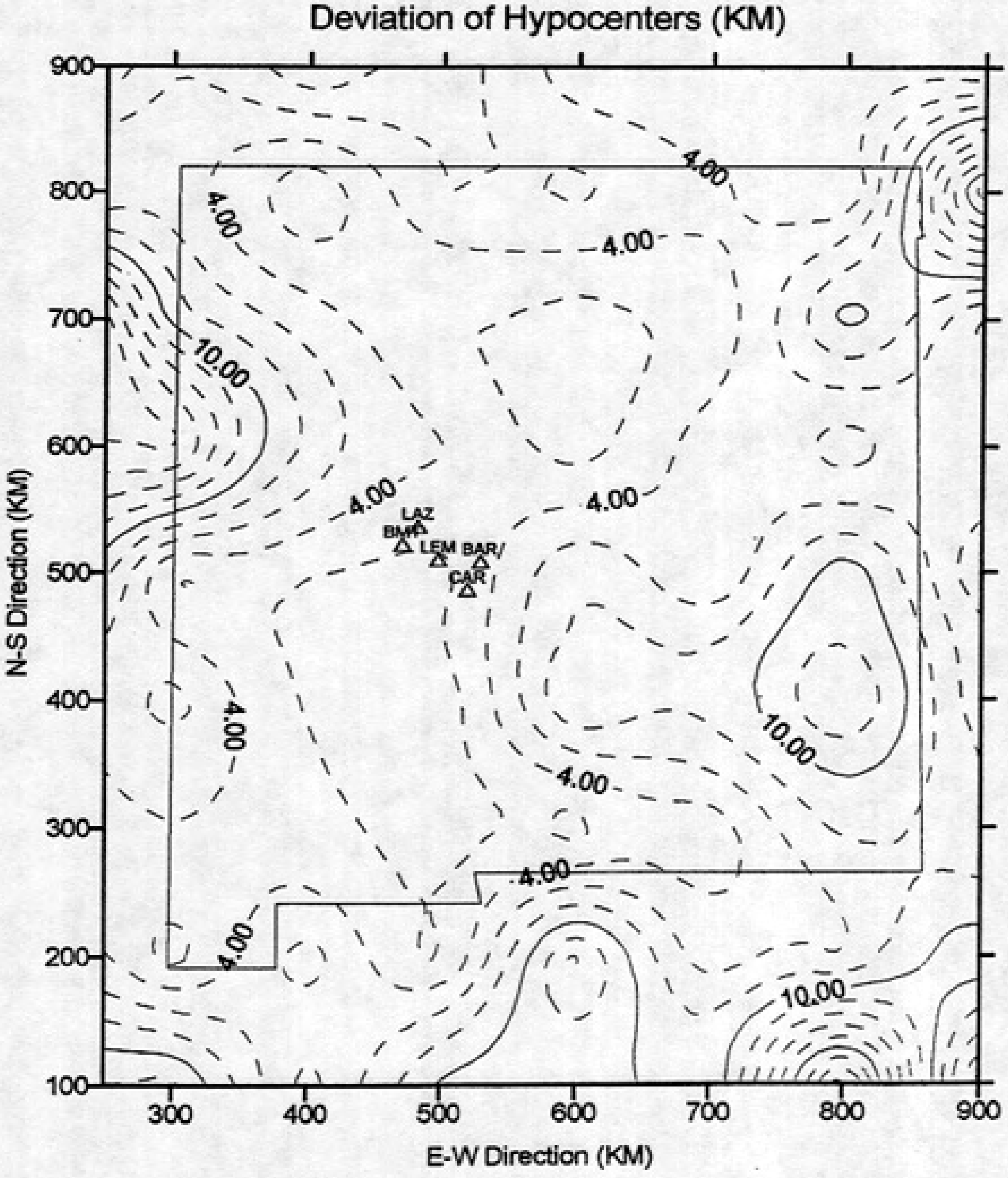

Figure 30d. The deviation (in km) of hypocenters of location program from synthetic hypocenters. The random background noise is ±0.5 seconds. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

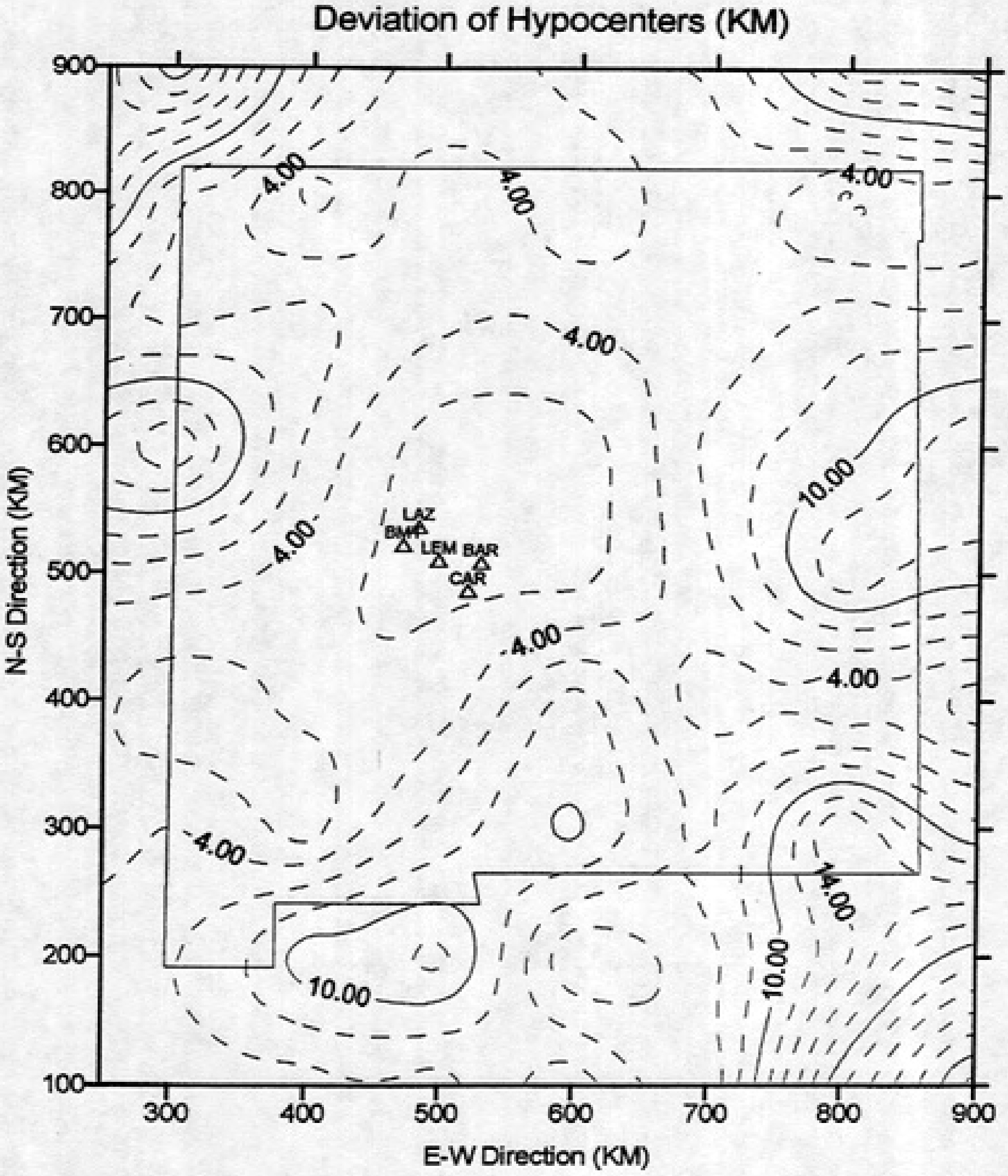

Figure 30e. The deviation (in km) of hypocenters of location program from synthetic hypocenters. The random background noise is ±0.5 seconds. BAR, BMT, CAR, LAZ, and LEM of Socorro seismic stations are used. Both SEISMOS and Fuzzy/SEISMOS programs produce the same results.

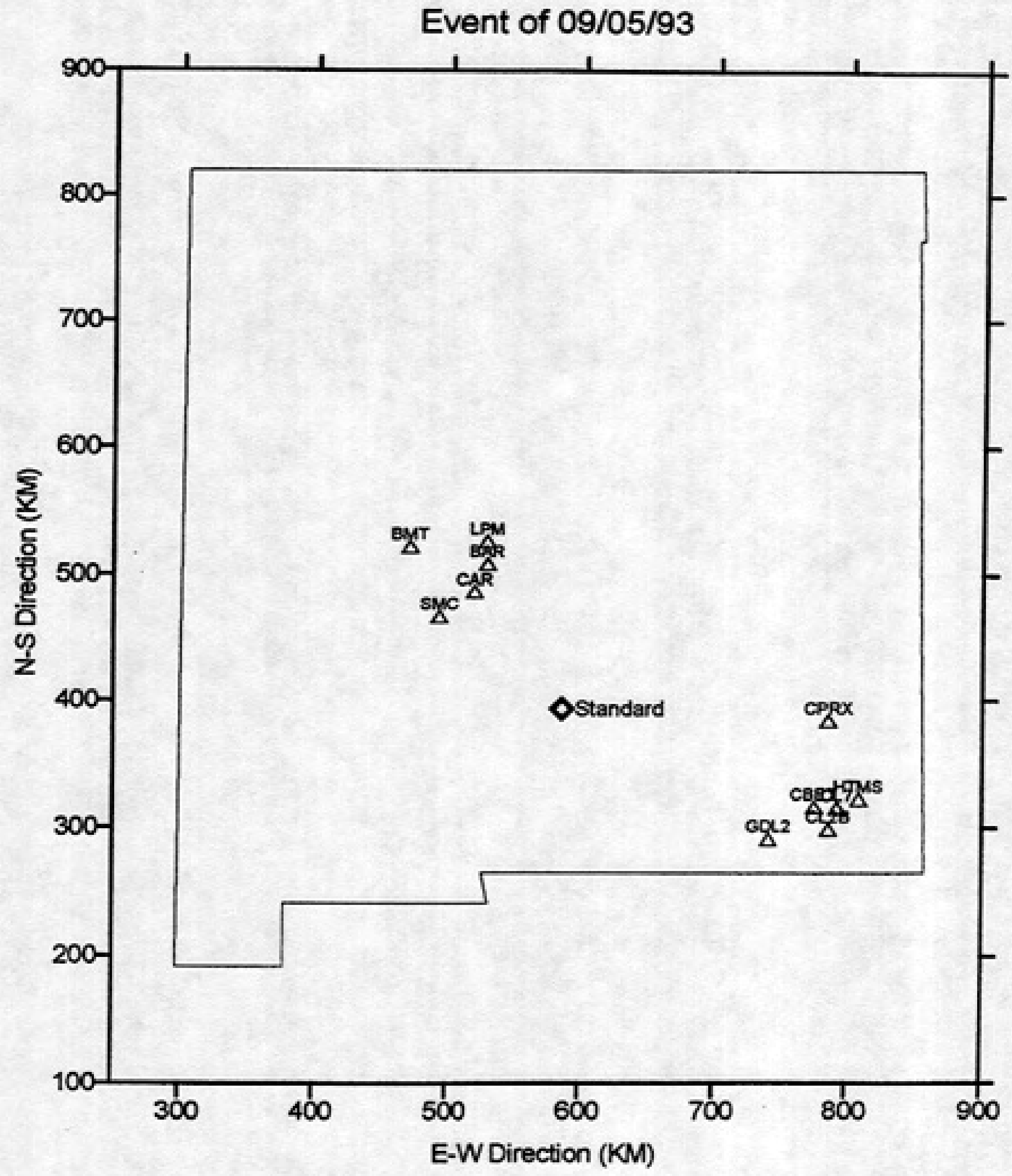

Figure 31a. The hypocenter (standard) solved by the SEISMOS program with phase readings from the two seismic networks.

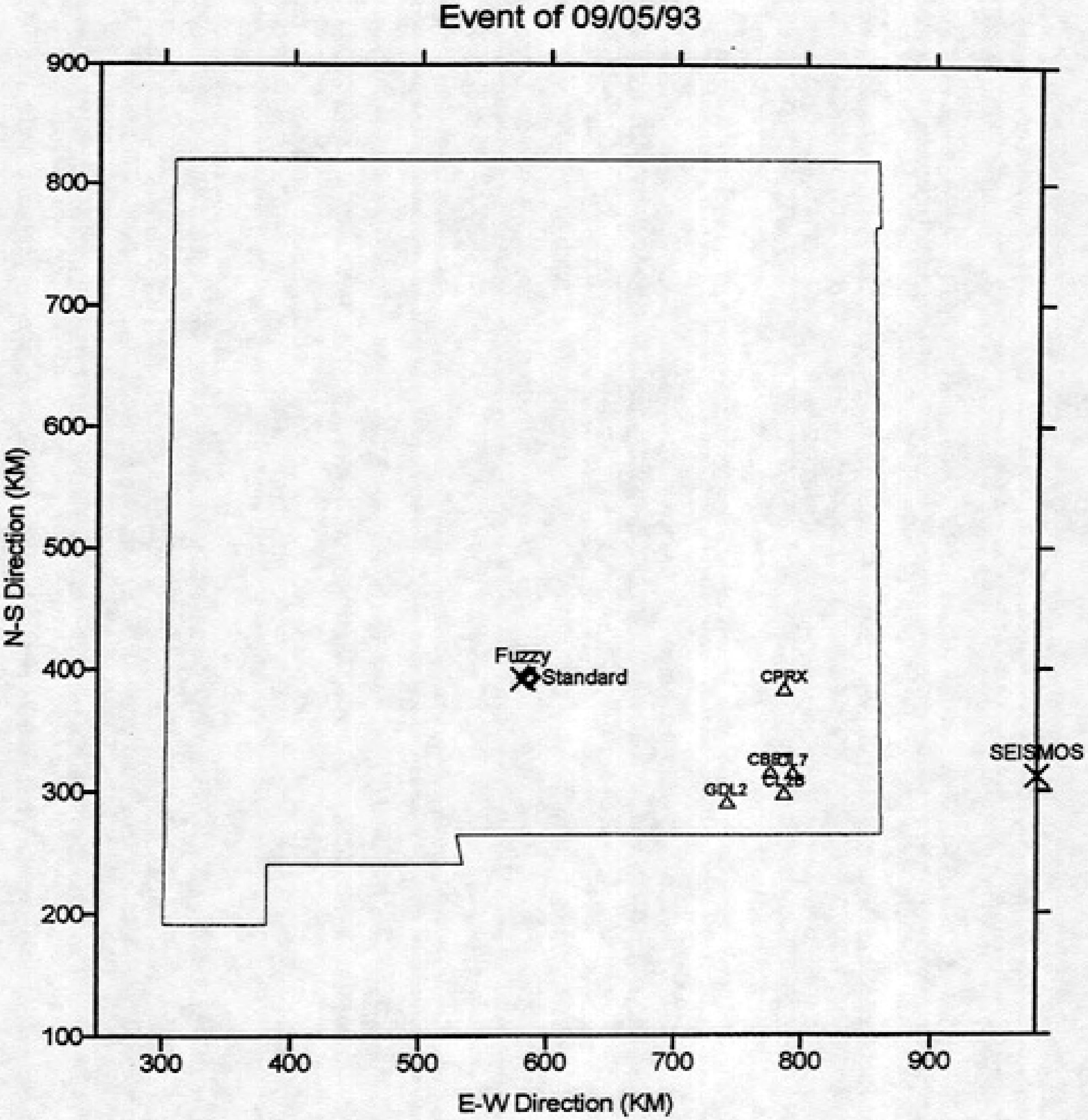

Figure 31b. The hypocenters solved by SEISMOS and Fuzzy/SEISMOS programs. Readings from all 6 WIPP seismic stations except HTMS are used. Note the large separation of the SEISMOS hypocenter from the standard.

However if the WIPP station HTMS is removed, the SEISMOS program calculates a hypocenter ~400 km from the standard whereas the Fuzzy/SEISMOS program produces a hypocenter near the standard (Figure 31b).

Figure 32a shows the standard hypocentral location and the Socorro and WIPP network station configurations for an event on September 9,1993. This event is almost in the same location as the previous example and is recorded by the same stations in each network. In this case, if all WIPP readings are used, the SEISMOS program calculates an epicenter which is ~400 km from the standard whereas the Fuzzy/SEISMOS produces a hypocenter near the standard (Figure 32b).

Figure 33 through 37 are for other events with different epicenters in the study area. As above, these figures show that hypocenters based on readings from two networks cannot be found by the SEISMOS program with readings from one network. On the other hand, the Fuzzy/SEISMOS program is successful under the same circumstances.

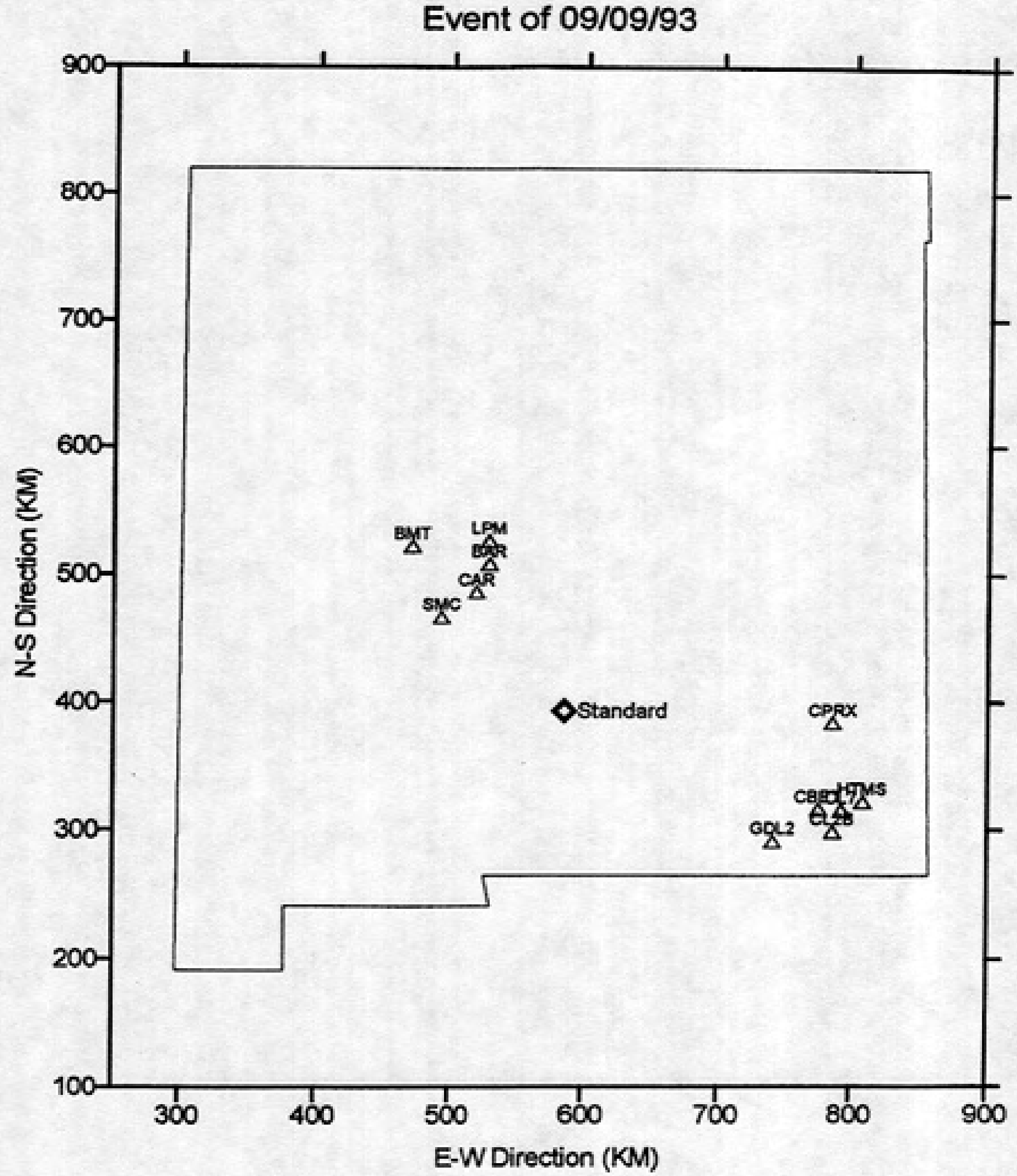

Figure 32a. The hypocenter (standard) solved by the SEISMOS program with phase readings from the two seismic networks.

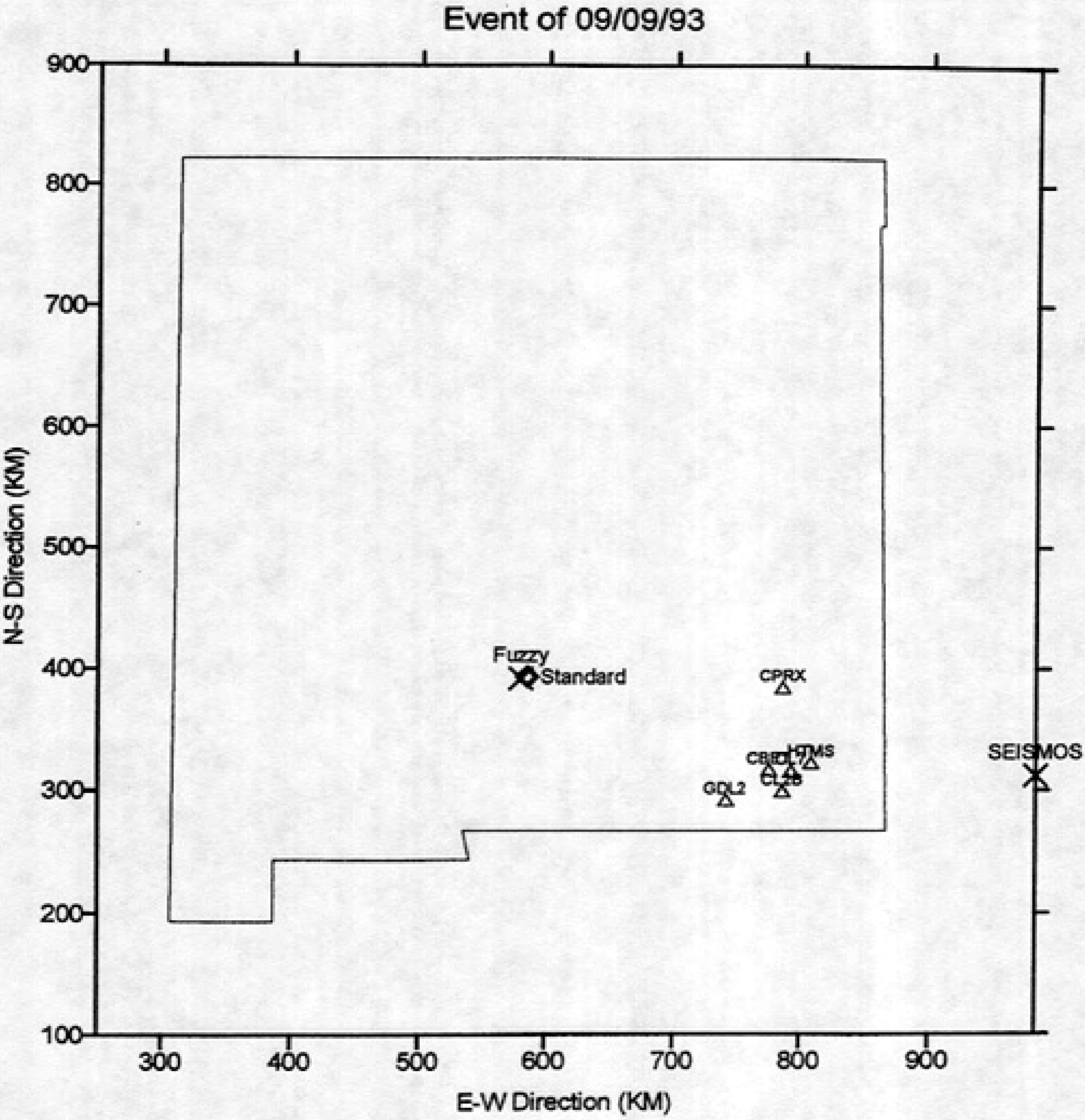

Figure 32b. The hypocenters solved by SEISMOS and Fuzzy/SEISMOS programs. All WIPP seismic station readings are used. Note the large separation of the SEISMOS hypocenter from the standard.

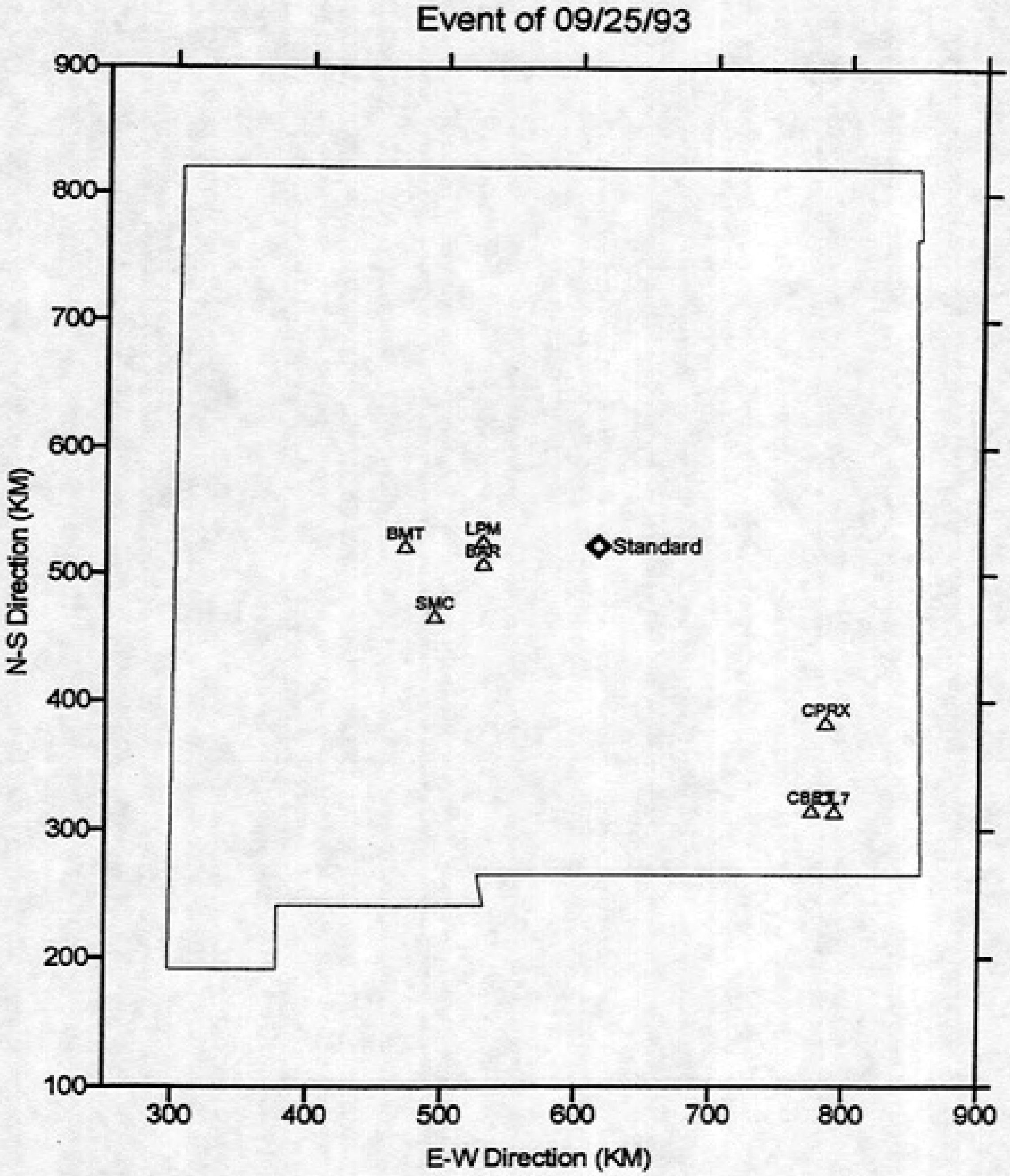

Figure 33a. The hypocenter (standard) solved by the SEISMOS program with phase readings from the two seismic networks.

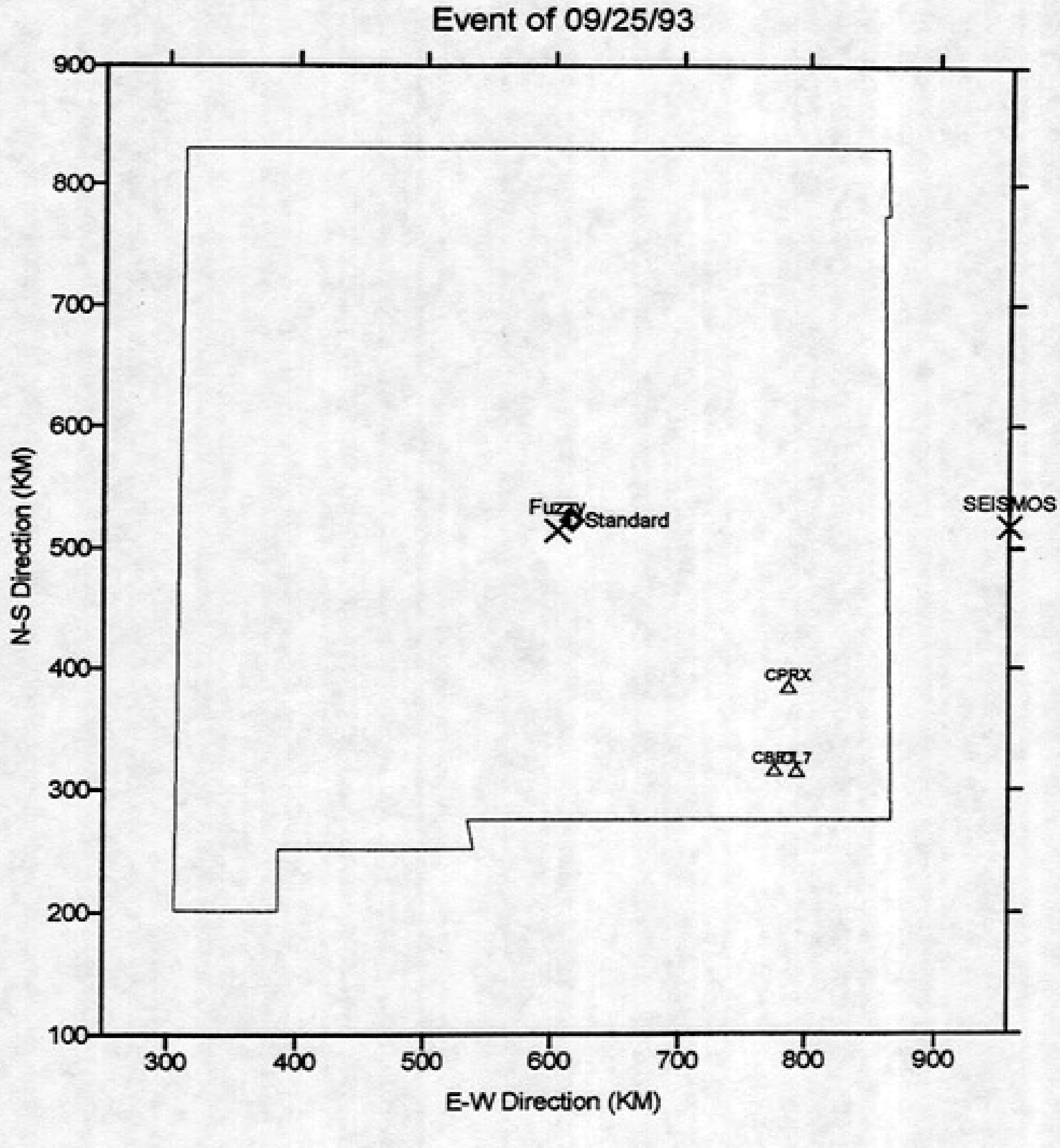

Figure 33b. The hypocenters solved by SEISMOS and Fuzzy/SEISMOS programs. All WIPP seismic station readings are used. Note the large separation of the SEISMOS hypocenter from the standard.

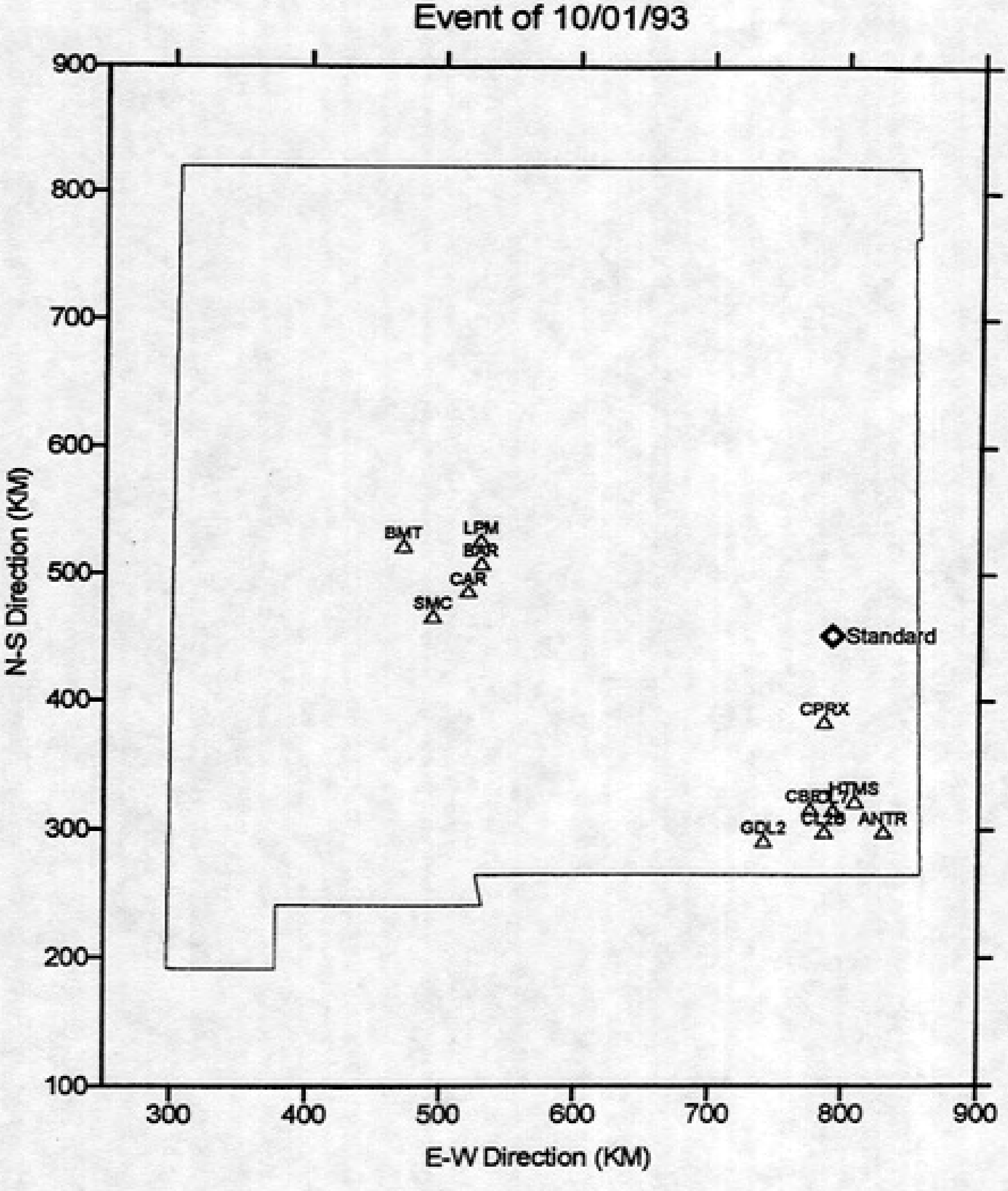

Figure 34a. The hypocenter (standard) solved by the SEISMOS program with phase readings from the two seismic networks.

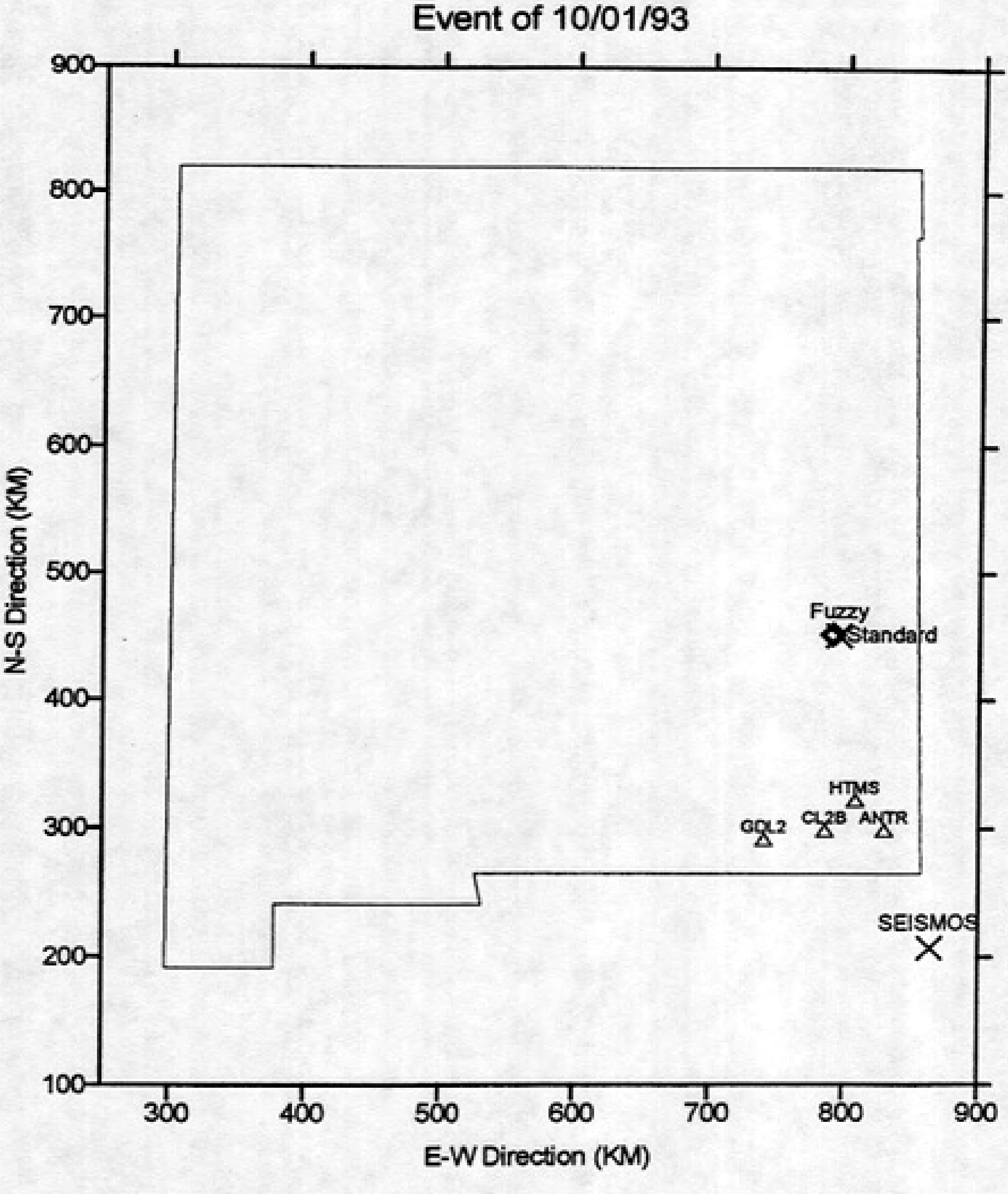

Figure 34b. The hypocenters solved by SEISMOS and Fuzzy/SEISMOS programs. Only WIPP seismic stations GDL2, CL2B, HTMS, and ANTR are used.

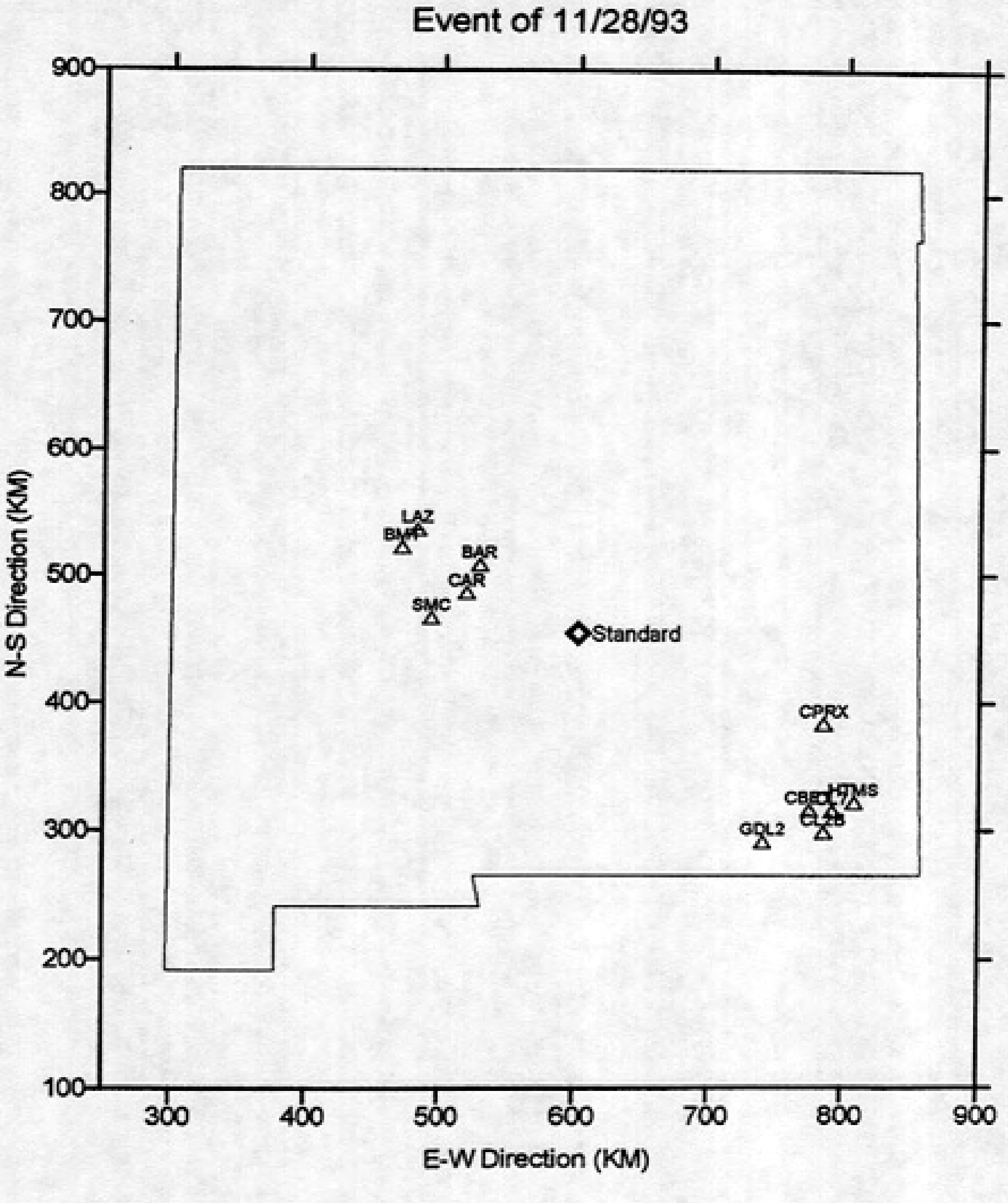

Figure 35a. The hypocenter (standard) solved by the SEISMOS program with phase readings from the two seismic networks.

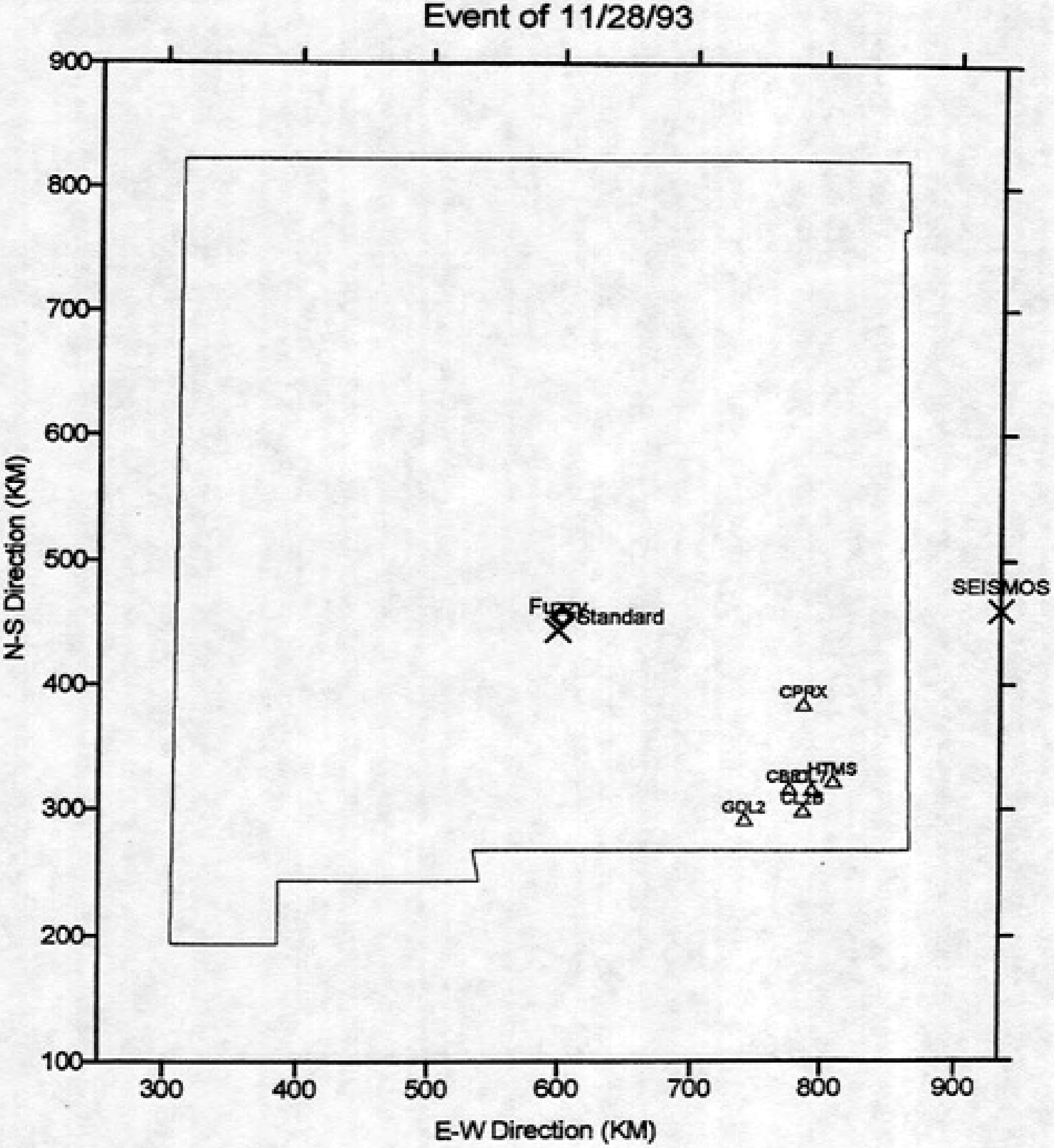

Figure 35b. The hypocenters solved by SEISMOS and Fuzzy/SEISMOS programs. All WIPP seismic station readings are used. Note the large separation of the SEISMOS hypocenter from the standard.

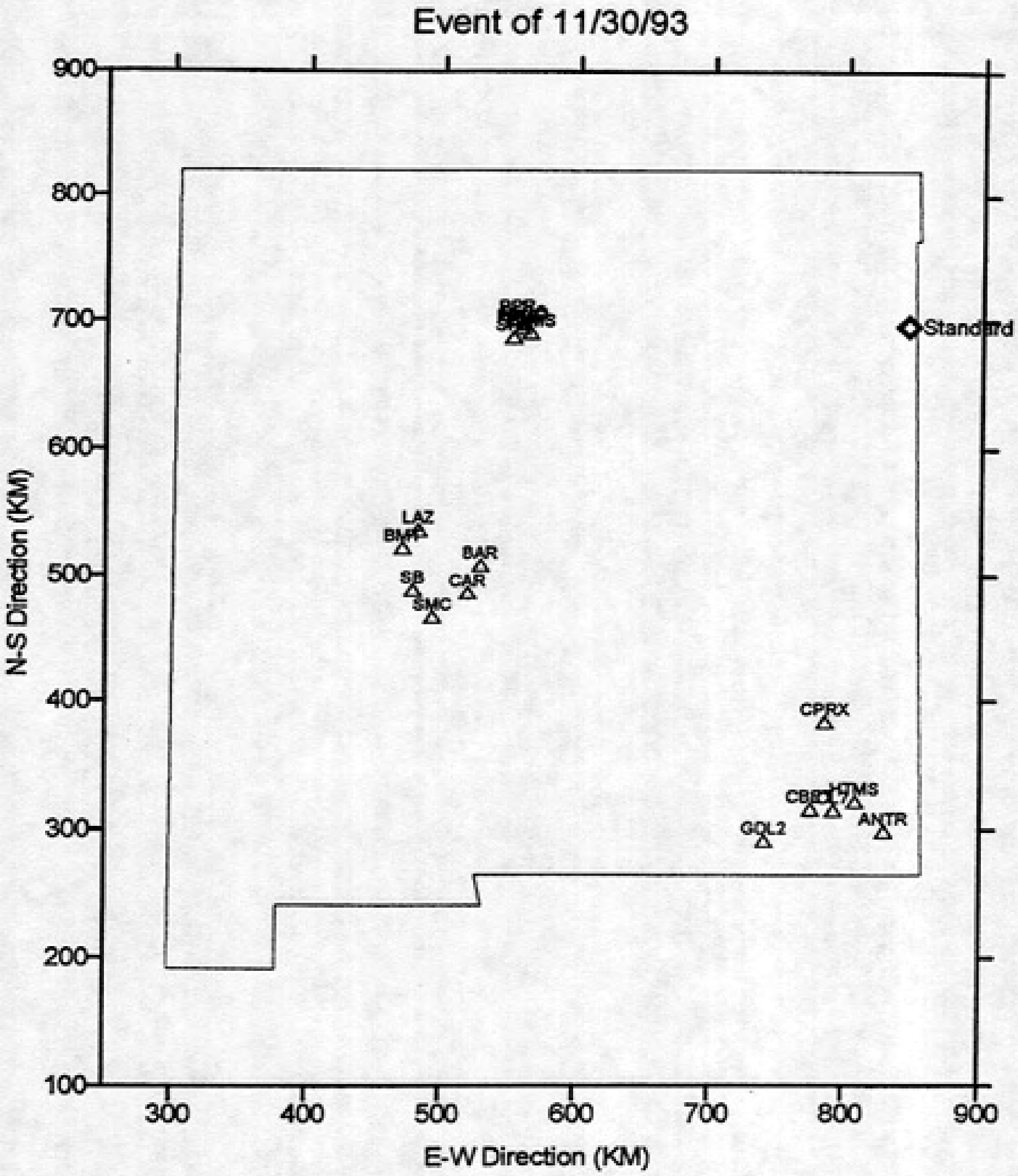

Figure 36a. The hypocenter (standard) solved by the SEISMOS program with phase readings from the three networks.

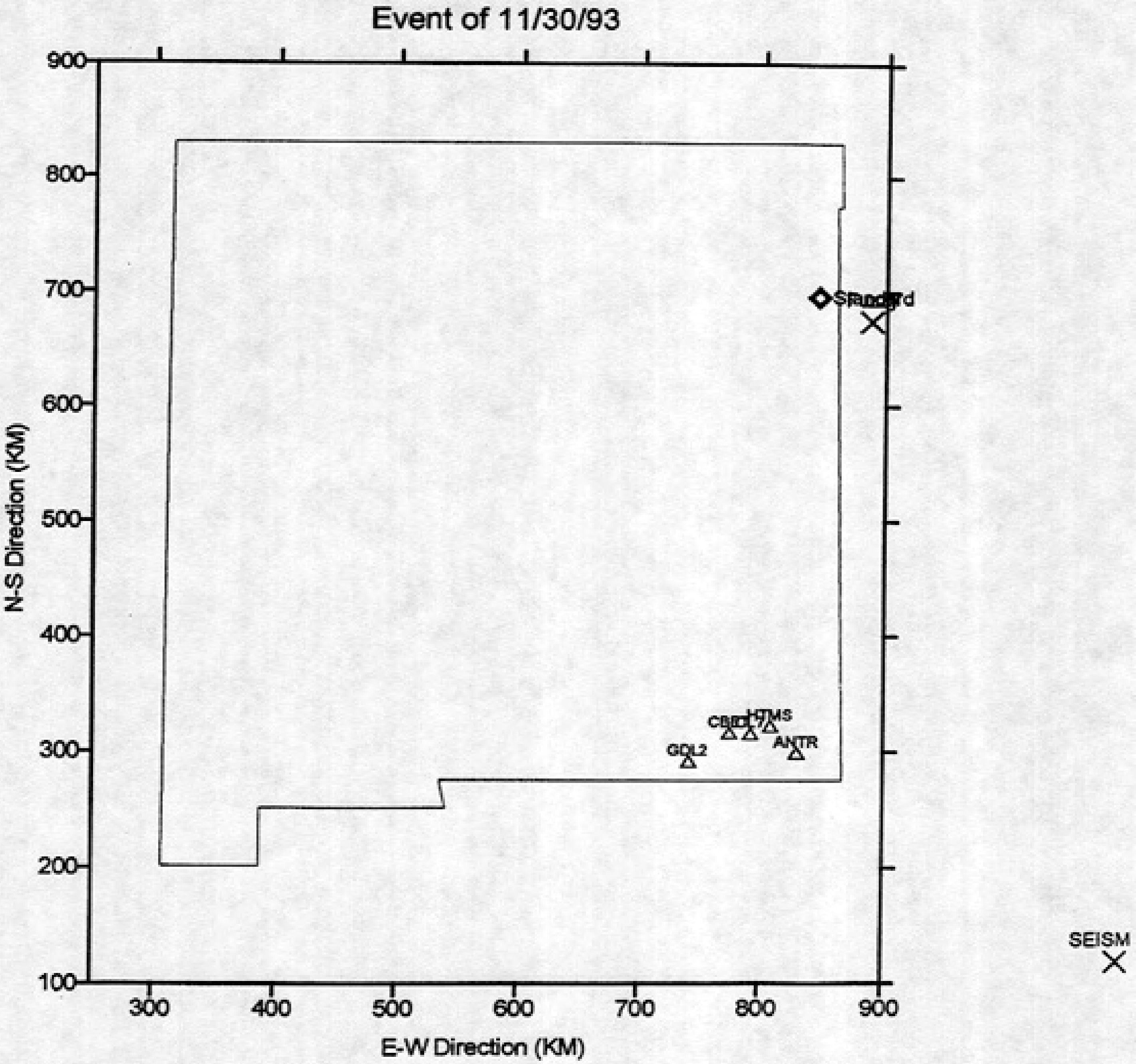

Figure 36b. The hypocenters solved by SEISMOS and Fuzzy/SEISMOS programs. All available WIPP seismic station readings except CPRX are used. Note the large separation of the SEISMOS hypocenter from the standard.

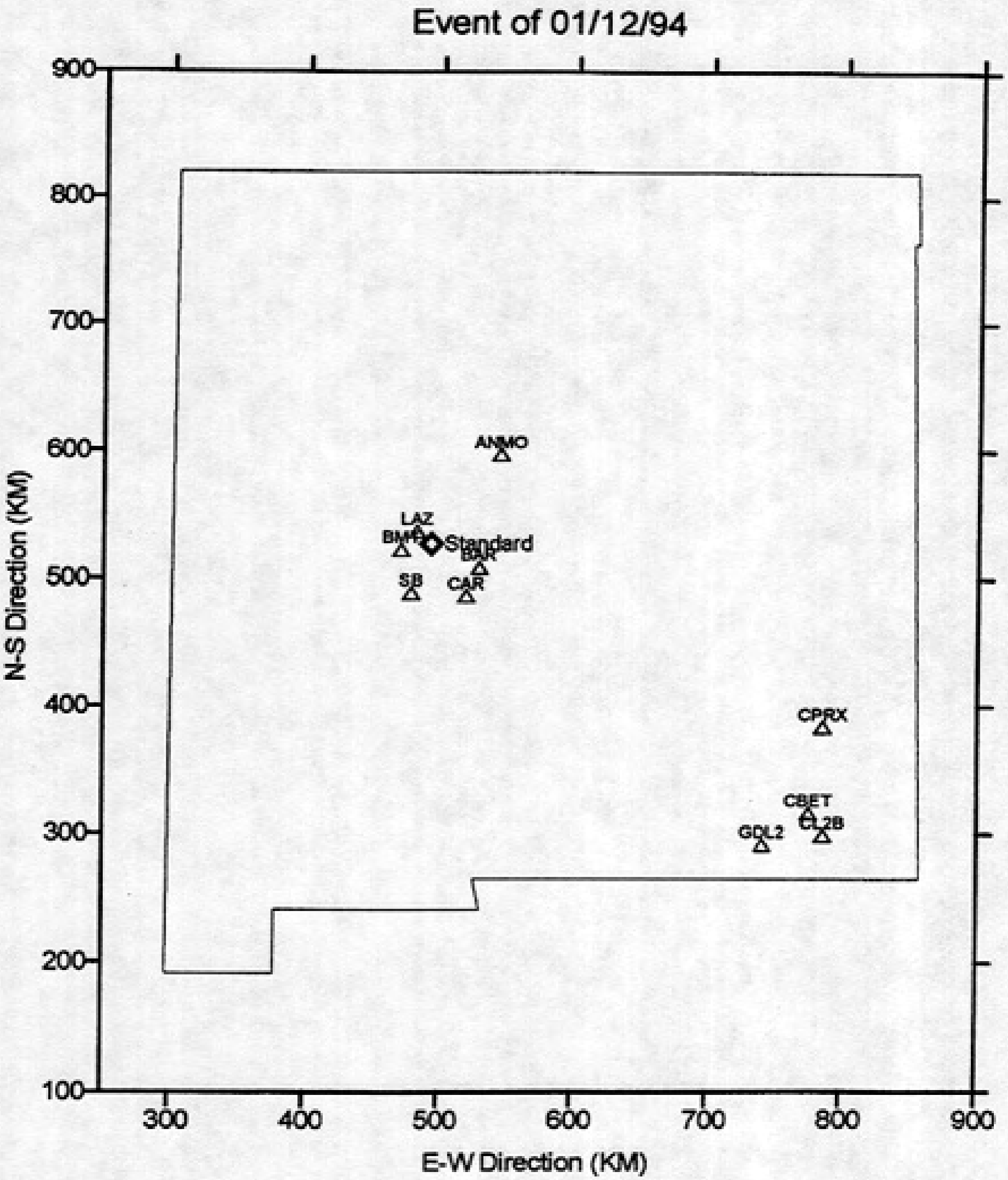

Figure 37a. The hypocenter (standard) solved by the SEISMOS program with phase readings from the two seismic networks and ANMO.

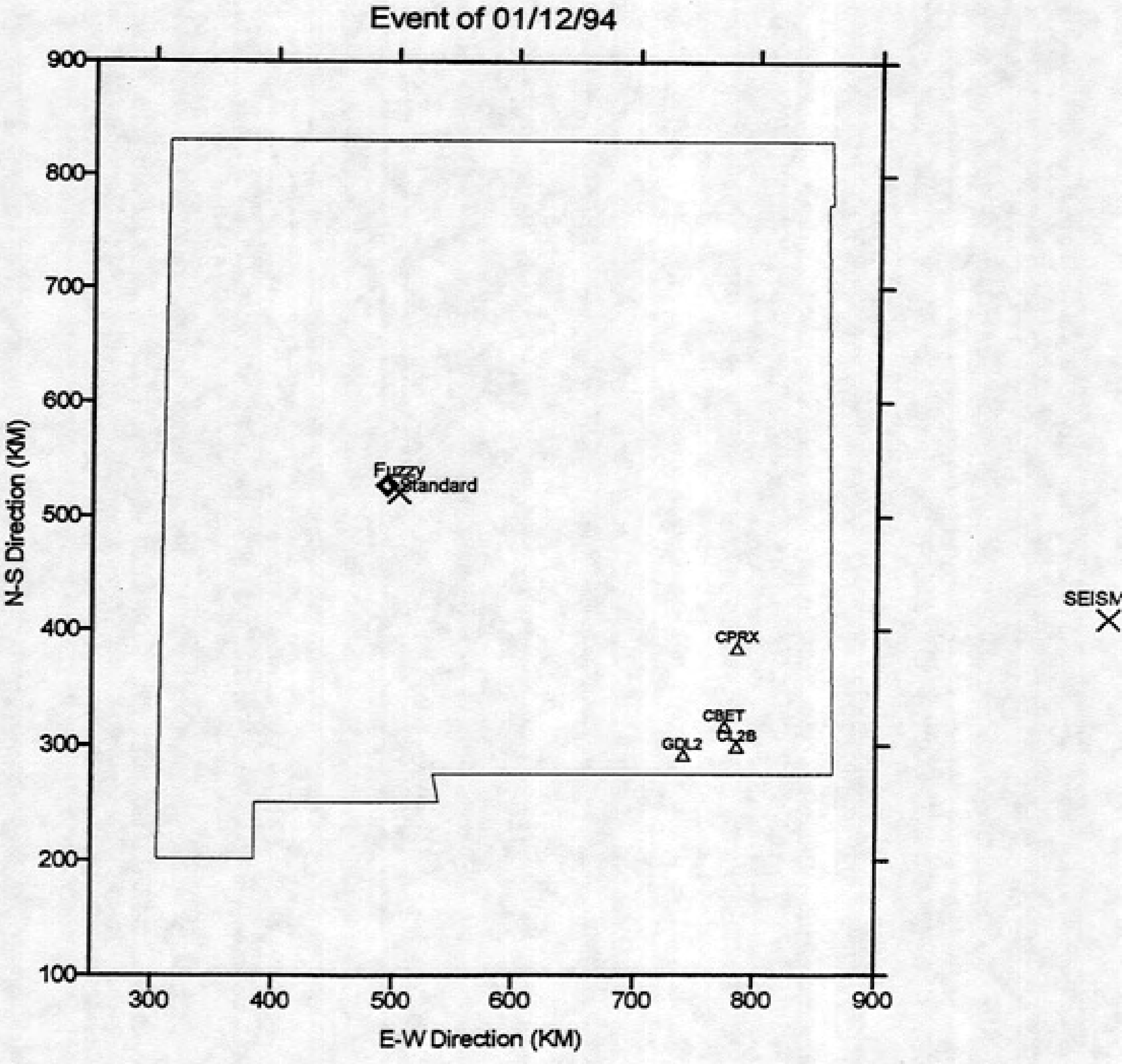

Figure 37b. The hypocenters solved by SEISMOS and Fuzzy/SEISMOS programs. All WIPP seismic station readings are used. Note the large separation of the SEISMOS hypocenter from the standard.

Discussion and Conclusion

A fuzzy logic earthquake location algorithm has been developed and incorporated into the currently used location program SEISMOS in the form of a initial hypocenter estimation subroutine. This subroutine performs a search over a very broad study area and focuses in on a preliminary epicenter. The coordinates of this estimated epicenter are used as a starting point for the iterative SEISMOS program. The SEISMOS program with the Fuzzy Location Algorithm subroutine has been designated the Fuzzy/SEISMOS location program.

Using synthetic data, I have tested the comparative effectiveness of the SEISMOS and Fuzzy/SEISMOS programs, to variations in (1) station geometry, (2) crustal velocity, (3) Poisson's ratio, and (4) background noise. Effectiveness was judged by the difference between hypocenters calculated by the programs and hypocenters used to generate the synthetic travel time data. In a surprisingly large number of the tests, (~ 40 %), the SEISMOS program failed to produce even approximately correct hypocenters in much of the study area. On the other hand, with the exception of three-station configurations, the Fuzzy/SEISMOS program yielded good estimates of the location of the synthetic epicenters throughout the study area.

Additional tests on the effectiveness of the two programs were made using real earthquake data from the two New Mexico Tech networks. Using data from both networks for seven different earthquakes throughout the study area, standard locations for purposes of comparison were established. These seven events were then located by combinations of stations from a single network. For these tests, the SEISMOS program calculated hypocenters from a few hundred to many hundred kilometers from the standard locations. On the other hand, the Fuzzy/SEISMOS program (with the same data sets) placed hypocenters very close to the standard locations.

Future Work

The fuzzy logic algorithm is an experience-oriented algorithm, and it could be improved with human experience. The current Fuzzy/SEISMOS program uses only four fuzzy sets, but these fuzzy sets are expandable. The present Fuzzy/SEISMOS program is design for locating regional earthquakes. We expect to modify the algorithm and use it to locate local earthquakes where information is limited.

References

1. Toppozada, T. M. R., Ph.D. Thesis, (1974). Seismic Investigation of Crustal Structure and Upper Mantle Velocity in the State of New Mexico and Vicinity, New Mexico Institute of Mining and Technology, New Mexico.

2. Singer, P. J., Ph.D. Thesis, (1989). Crustal Structure in the Socorro Area of the Rio Grande Rift from Time-Term Analysis, New Mexico Institute of Mining and Technology, New Mexico.

3. Hartse, H. E., Ph.D. Thesis, (1991). Simultaneous Hypocenter and Velocity Model Estimation Using Direct and Reflected Phases from Microearthquakes Recorded Within the Central Rio Grande Rift, New Mexico, New Mexico Institute of Mining and Technology, New Mexico.

4. Uhrhammer, R. A., (1980). Analysis of Small Seismographic Station Networks, Bull. Seism. Soc. Am. 70, 1369-1380.

5. Lee, W. H. K. and Lahr, J. C., (1975). HYPO71 (Revised): A Computer Program for Determining Hypocenter, Magnitude, and First Motion Pattern of Local Earthquakes, U.S. Geol. Surv., Open-File Report 75-311, 77 pp.

6. Jamshidi, M., Vadiee, N., and Ross, T. J., Editors, (1993). Fuzzy Logic and Control Software and Hardware Applications, PTR Prentice-Hall Inc., New Jersey.

7. Yager, R. R., Zadeh, L. A., (1992). An Introduction to fuzzy logic applications in intelligent systems, Kluwer Academic, Boston.

8. Zadeh, L. A., Kacprzyk, J., (1992). Fuzzy logic for the management of uncertainty, Wiley, New York.