INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/709-16

Second Workshop on Non-Linear Dynamics and Earthquake Prediction

22 November - 10 December 1993

Changes of Seismicity in the Western United States Preceding the Landers Earthquake on June 28, 1992: Case History and Current State of the M8 Predictions

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Changes of seismicity in the western United States preceding the Landers earthquake on June 28, 1992: Case history and current state of the M8 predictions.

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Abstract.

Premonitory phenomena, both for M ≥ 7.5 and M ≥ 7.0 earthquakes, were recognized by the M8 algorithm in seismicity of the western United States. The Landers earthquake falls within space and time of these predictions. However this earthquake falls off the times of increased probability (TIP) announced in the Test of M8 (Healy et al., 1992) where we have used a simple null-hypothesis, and, therefore, a rarified set of circles of investigation. Were the Test of M8 be made for a denser set of circles the Landers earthquake would not be missed.

The premonitory phenomena were composed by the general increase of seismic activity on both sides of the great Central Valley, and can be associated with the Coalinga, Morgan Hill, Mammoth Lakes, Chalfant Valley, Narrows Whittier, and Superstition Hills earthquakes. The Loma Prieta, off-shore Oregon, Ferndale, and Landers earthquakes, all above magnitude 7.0, followed this activation.

The current state of the M8 algorithm predictions in the western United States depends strongly on whether or not we accept the rule that terminates an alarm after a strong earthquake. In the Test of M8 (Healy et. a., 1992) we rejected this rule on the basis of global statistics - each third earthquake with M ≥ 7.5 is accompanied by another such earthquake within four years and 250 km vicinity. However there were no evidence of pairing of M > 7.25 earthquakes in the seismic history of the western United States.

The current state of predictions by the Test of M8 standards is the following:
- The M8 algorithm gives no current alarms for an 8.0+ earthquake.
- The alarm for a 7.5+ earthquake expires on January 1, 1994.
- The alarm for a 7.0+ earthquake expires on January 1, 1995.
The territorial limits of these predictions are defined below.

Introduction.

Each major earthquake opens the question among scientific community: was it preceded by some phenomena which can be regarded as premonitory to this earthquake? The "precursors" which have been defined previously would be of particular interest as each additional case history tests their significance and reliability.

Here we explore this question for a set of spatial and temporal variations of seismicity prior to the Landers earthquake on June 28, 1992. This is the strongest earthquake in the Western United States for the last forty years. Out of all suggested "precursors" we consider one specific set of variations of seismicity in space and time used in the M8 algorithm (Keilis-Borok, Kossobokov, 1986, 1990; Healy et al., 1992). This algorithm was previously applied to seismic regions worldwide, including the western United States.

We take advantage of the study presented in (Healy et al., 1992) where the data base and computer code of the algorithm were specified exactly for a global Test of M8.

Measures of seismicity used in the M8 algorithm.

According to this algorithm, the territory under consideration is scanned by overlapping circles of investigation. The Time of Increased Probability for an earthquake with $M \geq M_0$ (acronymed as "TIP") is diagnosed in each circle independently on the basis of analysis of transient seismicity in the lower magnitude ranges. A TIP is declared for five years, and could be both extended or canceled by analysis of the up-to-dated catalog. The radii of circles depend on M_0, e.g. for magnitudes M_0 = 7.0, 7.5, and 8.0 they are 281, 427, and 667 km respectively.

In each circle we count four integrated measures of transient seismicity (Keilis-Borok, Kossobokov, 1986; 1990) -
- "activity" - a trailing average of the number of earthquakes, N;
- deviation of "activity" from its long term average - a difference between actual value of N and its prediction by linear extrapolation from the preceding time, L;
- "linear concentration of earthquake sources" - a ratio of a trailing average size of an earthquake source to an average distance between them, Z;

- "burst of aftershocks" - a trailing maximal number of aftershocks in a population of moderate main shocks, B.

These measures are functions of time, t. They are defined on a sliding interval from (t-s) to t. (s = 6 years for the first three measures, and s = 1 year for B). In the first three measures we count main shocks only. We do it twice for different lower magnitude cutoffs. These cutoffs are just sufficient to provide an annual average of 10 and 20 main shocks in a circle. In the last two measures, Z and B, large earthquakes are not considered to avoid their predomination.

The formal unambiguous definition of these measures and the M8 algorithm is given in the computer code and standard profiles (Healy et al., 1992). The M8 algorithm and the results of its testing are described in more detail in (Keilis-Borok, Kossobokov, 1990; Healy et al., 1992).

Seismicity prior to the Landers earthquake.

Let us consider each of the above-mentioned measures of seismicity using the same data base and computer code as in (Healy et al., 1992) in one specific circle. The circle is centered at 35°N, 119°W and has R = 427 km. It encompasses two thirds of California south from the Bay of San Francisco, and, obviously, the epicentral zone of the Landers earthquake. Same as in the Test of M8, measures are counted on each semi-annual from July 1, 1975 to July 1, 1992. The algorithm determined magnitude cutoffs for the circle to be 4.5 and 4.1, respectively.

Figure 1 shows how the measures changed in time. The measures of "activity", N1 and N2, have reached maxima in 1985-1987 and remain rather high until 1990. Similar behavior characterizes their deviations from long term trends, L1 and L2. Linear concentrations, Z1 and Z2, show remarkable correlation: they have reached local maxima on July 1, 1984, drop down in 1986, and then came to their absolute maxima on January 1, 1989. The last measure, B, has maximum value of 46 in 1987, that is the number of $M \geq 4.0$ aftershocks of the Chalfant Valley, 1986 earthquake in the first two weeks after the main shock. Thus, the measures were at their top values in 1987 - a pattern recognized as premonitory by the M8 algorithm. By formal determination the period from July 1, 1988 to

July 1, 1993 in the circle is the TIP of a M ≥ 7.5 earthquake, and the Landers earthquake does fall into it.

Let us consider two other circles with the same center. Both contain epicenter of the Landers earthquake. The first, having the radius of 281 km, is used by the M8 algorithm compiled to predict magnitude 7.0+ earthquakes. In this case, we have to expand the data base used in (Healy et. al., 1992) taking into consideration all magnitude 3.0 and above earthquakes from the NEIC Global Hypocenters Data Base as it was done earlier (Keilis-Borok, Kossobokov, 1988, 1990). The magnitude cutoffs in the circle are 4.0 and 3.6. Figure 2 shows the variation of measures in 1975-1992. The behavior of functions N and L is similar to what was observed above in a larger circle. The functions Z show rather steady growth to the maxima on July 1, 1989. Thus, the TIP for magnitude 7.0+ is defined from January 1, 1990 to January 1, 1995, and contains the Landers earthquake as well.

The second circle has the 667 km radius, used by the M8 algorithm to predict magnitude 8.0+ earthquakes. The magnitude cutoffs in it are 4.7 and 4.2, respectively. Despite small differences in values of magnitude cutoffs the behavior of functions is somewhat different from that in circle of 427 km radius (Figure 3). The maxima of N, L, and B appeared in 1980, following the Imperial Valley, 1979 earthquake, however the maxima of Z functions was observed in 1990 after the Loma Prieta, 1989 earthquake. Thus, no TIP was diagnosed. Moreover, the extremely low values of N and L functions suggest that no TIP will be diagnosed in the near future.

The territory of the TIP's.

Let us now outline the limits of the alarm in the western United States. For this purpose we ran the algorithm in 103 circles. These are all the circles with centers at integer latitudes and longitudes in the western United States where the data are sufficient for application of the algorithm by the Test of M8 standards (Healy et. al., 1992): the algorithm will not run if the annual average number of main shocks of M ≥ 4.0 is fewer than 16.

The results of simulated forward prediction over such a dense set of circles are summarized in Table 1 below. We see that in the last

Figure 2.

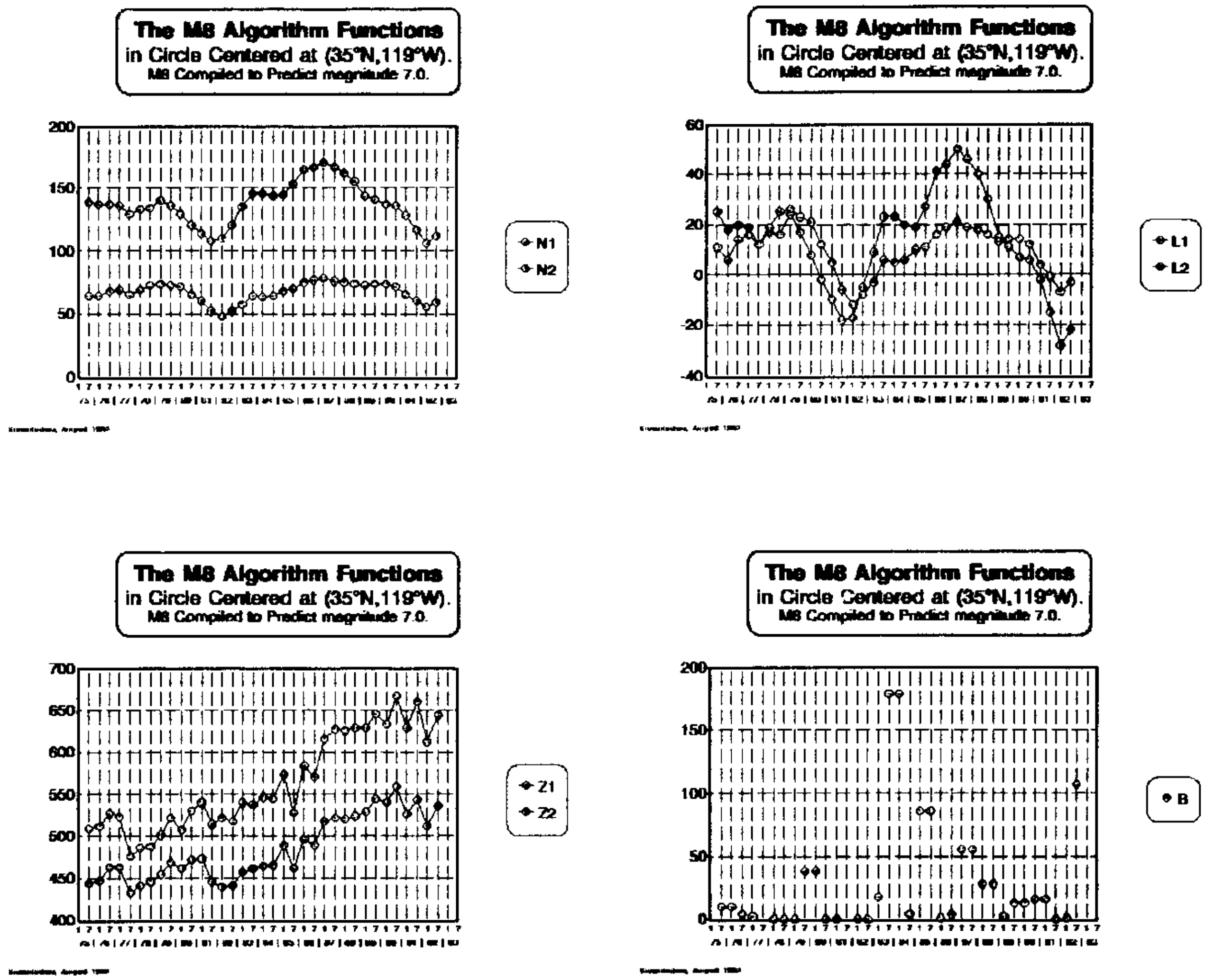
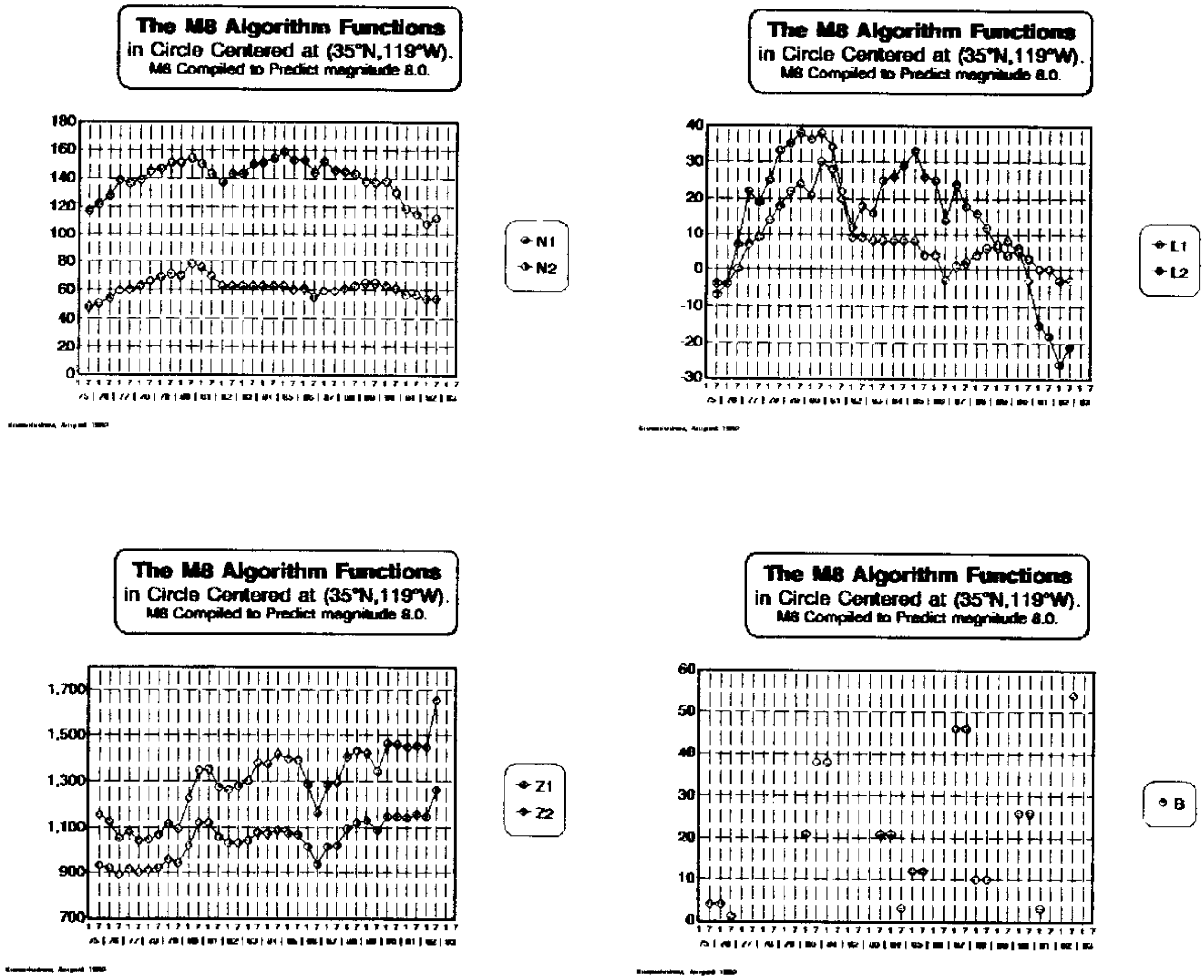

The M8 Algorithm Functions
in Circle Centered at (35°N,119°W).
M8 Compiled to Predict magnitude 7.0.
N1
N2
The M8 Algorithm Functions
in Circle Centered at (35°N,119°W).
M8 Compiled to Predict magnitude 7.0.
L1
L2
The M8 Algorithm Functions
in Circle Centered at (35°N,119°W).
M8 Compiled to Predict magnitude 7.0.
Z1
Z2
The M8 Algorithm Functions
in Circle Centered at (35°N,119°W).
M8 Compiled to Predict magnitude 7.0.
B

Figure 3.


The M8 Algorithm Functions
in Circle Centered at (35°N,119°W).
M8 Compiled to Predict magnitude 8.0.
N1
N2
The M8 Algorithm Functions
in Circle Centered at (35°N,119°W).
M8 Compiled to Predict magnitude 8.0.
L1
L2
The M8 Algorithm Functions
in Circle Centered at (35°N,119°W).
M8 Compiled to Predict magnitude 8.0.
Z1
Z2
The M8 Algorithm Functions
in Circle Centered at (35°N,119°W).
M8 Compiled to Predict magnitude 8.0.
B

update prior to the Landers earthquake (on January 1, 1992) eight circles were in state of alarm, four of them predicted the Landers earthquake. The territory of alarm is shown in Figure 4. It encompasses most of California and adjacent regions of Nevada. Two magnitude 7.1 earthquakes - the Loma Prieta, 1989 and Ferndale, 1992 - have occurred in the northern portion of alarm which expired on July 1, 1992.

The M8 algorithm compiled to predict magnitude 7.0+ earthquakes outlines about the same seismic zone (Figure 5). Its northern portion predicted the Loma Prieta earthquake (Keilis-Borok et al., 1990) and will expire on January 1, 1993, while the southern portion predicted the Landers earthquake and will expire on January 1, 1995.

Similar analysis by the M8 algorithm compiled to predict $M \geq 8.0$ earthquakes gives no TIP in the western United States.

The conclusions are subject to updating of the data base and analysis each semiannual.

Additional testing.

We have performed a number of runs trying to evaluate the stability of the results. Among them exclusion of some specific main shocks with their aftershocks or all earthquakes from an area. These experiments have shown the significant role of the Chalfant Valley, 1986 earthquake in the prediction. Without it the occurrence of the premonitory phenomena would not be so clear. When we separated the seismicity considered into two parts - San Andreas fault zone and Sierra Nevada - we found that both contribute to declaration of the TIP's. We have found also that the territory of alarm does not change much when we include explosions or exclude all the seismicity of the Nevada Test Site. Altogether these runs show stability of the prediction.

Table 1. Distribution of TIP's in the western United States.

The symbols in the table indicate the status of each circle of investigation in six-month intervals from January 1, 1988 to July 1, 1992:

▓ indicates a TIP, . indicates no TIP,
■ indicates a prediction, [*] indicates a strong earthquake

Coordinates		88 a	88 b	89 a	89 b	90 a	90 b	91 a	91 b	92 a	92 b
34.00	-120.00	▓	▓	▓	▓	▓	▓	▓	▓	■	▓
34.00	-119.00	.	.	.	.	.	.	.	.	[*]	.
34.00	-118.00	.	.	.	.	.	.	.	.	[*]	.
34.00	-117.00	.	.	.	.	.	.	.	.	[*]	.
34.00	-116.00	.	.	.	.	.	.	.	.	[*]	.
34.00	-115.00	.	.	.	.	.	.	.	.	[*]	.
35.00	-121.00	▓	▓	▓	▓	▓	▓	▓	▓	■	▓
35.00	-120.00	▓	▓	▓	▓	▓	▓	▓	▓	■	▓
35.00	-119.00	▓	.	.	.	.	.	.	.	■	▓
35.00	-118.00	.	.	.	.	.	.	.	.	[*]	.
35.00	-117.00	.	.	.	.	.	.	.	.	[*]	.
35.00	-116.00	.	.	.	.	.	.	.	.	[*]	.
35.00	-115.00	.	.	.	.	.	.	.	.	[*]	.
36.00	-121.00	▓	▓	▓	▓	▓	▓	▓	▓	▓	.
36.00	-120.00	▓	▓	.	.	.	.	▓	.	[*]	.
36.00	-119.00	▓	▓	▓	▓	▓	▓	.	.	[*]	.
36.00	-118.00	.	.	.	.	.	.	.	.	[*]	.
36.00	-117.00	.	.	.	.	.	.	.	.	[*]	.
36.00	-116.00	.	.	.	.	.	.	.	.	[*]	.
36.00	-115.00	.	.	.	.	.	.	.	.	[*]	.
37.00	-122.00	▓	▓	▓	▓	▓	▓	▓	▓	▓	.
37.00	-121.00	▓	▓	▓	▓	▓	▓	▓	▓	▓	.
37.00	-120.00	▓	▓	▓	▓	▓	▓	▓	.	.	.
37.00	-119.00	▓	.	.	.	.	.	▓	.	[*]	.
37.00	-118.00	▓	▓	▓	▓	.	.	.	.	[*]	.
37.00	-117.00	▓	▓	▓	▓	▓	.	.	.	[*]	.
37.00	-116.00	.	.	.	.	.	.	.	.	[*]	.
38.00	-124.00	.	.	.	.	.	.	.	.	.	.
38.00	-123.00	.	.	.	.	.	.	.	.	.	.
38.00	-122.00	▓	▓	▓	▓	▓	▓	▓	▓	▓	.
38.00	-121.00	▓	▓	▓	▓	.	.	.	.	.	.
38.00	-120.00	▓	▓	▓	▓	.	.	.	.	.	.
38.00	-119.00	▓	▓	▓	▓	▓	.	.	.	.	.
38.00	-118.00	▓	▓	▓	▓	▓	.	.	.	.	.
38.00	-117.00	▓	▓	▓	▓	.	.	.	.	[*]	.
39.00	-126.00	.	.	.	.	.	.	.	.	.	.
39.00	-125.00	.	.	.	.	.	.	.	.	.	.
39.00	-124.00	.	.	.	.	.	.	.	.	.	.
39.00	-123.00	.	.	.	.	.	.	.	.	.	.
39.00	-122.00	.	.	.	.	.	.	.	.	.	.
39.00	-121.00	.	.	.	.	.	.	.	.	.	.
39.00	-120.00	▓	.	.	.	.	.	.	.	.	.
39.00	-119.00	▓	▓	▓	▓	.	.	.	.	.	.
39.00	-118.00	▓	▓	▓	▓	.	.	.	.	.	.
40.00	-129.00	.	.	.	.	.	.	.	.	.	.
40.00	-128.00	.	.	.	.	.	.	.	.	.	.
40.00	-127.00	.	.	.	.	.	.	.	.	.	.
40.00	-126.00	.	.	.	.	.	.	.	.	.	.
40.00	-125.00	.	.	.	.	.	.	.	.	.	.
40.00	-124.00	.	.	.	.	.	.	.	.	.	.
40.00	-123.00	.	.	.	.	.	.	.	.	.	.
40.00	-122.00	▓	.	.	.	.	.	.	.	.	.
40.00	-121.00	▓	▓	▓	▓	.	.	.	.	.	.
40.00	-120.00	.	.	▓	▓	.	.	.	.	.	.
40.00	-119.00	.	.	.	.	.	.	.	.	.	.

Coordinates		88 a	88 b	89 a	89 b	90 a	90 b	91 a	91 b	92 a	92 b
41.00	-130.00	.	.	.	.	.	.	.	.	.	.
41.00	-129.00	.	.	.	.	.	.	.	.	.	.
41.00	-128.00	.	.	.	.	.	.	.	.	.	.
41.00	-127.00	.	.	.	.	.	.	.	.	.	.
41.00	-126.00	.	.	.	.	.	.	.	.	.	.
41.00	-125.00	.	.	.	.	.	.	.	.	.	.
41.00	-124.00	.	.	.	.	.	.	.	.	.	.
41.00	-123.00	.	.	.	.	.	.	.	.	.	.
41.00	-122.00	.	.	.	.	.	.	.	.	.	.
42.00	-130.00	.	.	.	.	.	.	.	.	.	.
42.00	-129.00	.	.	.	.	.	.	.	.	.	.
42.00	-128.00	.	.	.	.	.	.	.	.	.	.
42.00	-127.00	.	.	.	.	.	.	.	.	.	.
42.00	-126.00	.	.	.	.	.	.	.	.	.	.
42.00	-125.00	.	.	.	.	.	.	.	.	.	.
42.00	-124.00	.	.	.	.	.	.	.	.	.	.
42.00	-123.00	.	.	.	.	.	.	.	.	.	.
42.00	-122.00	.	.	.	.	.	.	.	.	.	.
43.00	-130.00	.	.	.	.	.	.	.	.	.	.
43.00	-129.00	.	.	.	.	.	.	.	.	.	.
43.00	-128.00	.	.	.	.	.	.	.	.	.	.
43.00	-127.00	.	.	.	.	.	.	.	.	.	.
43.00	-126.00	.	.	.	.	.	.	.	.	.	.
43.00	-125.00	.	.	.	.	.	.	.	.	.	.
43.00	-124.00	.	.	.	.	.	.	.	.	.	.
43.00	-123.00	.	.	.	.	.	.	.	.	.	.
43.00	-122.00	.	.	.	.	.	.	.	.	.	.
44.00	-130.00	.	.	.	.	.	.	.	.	.	.
44.00	-129.00	.	.	.	.	.	.	.	.	.	.
44.00	-128.00	.	.	.	.	.	.	.	.	.	.
44.00	-127.00	.	.	.	.	.	.	.	.	.	.
44.00	-126.00	.	.	.	.	.	.	.	.	.	.
44.00	-125.00	.	.	.	.	.	.	.	.	.	.
44.00	-124.00	.	.	.	.	.	.	.	.	.	.
45.00	-129.00	.	.	.	.	.	.	.	.	.	.
45.00	-128.00	.	.	.	.	.	.	.	.	.	.
45.00	-127.00	.	.	.	.	.	.	.	.	.	.
45.00	-126.00	.	.	.	.	.	.	.	.	.	.
45.00	-125.00	.	.	.	.	.	.	.	.	.	.
46.00	-129.00	.	.	.	.	.	.	.	.	.	.
46.00	-128.00	.	.	.	.	.	.	.	.	.	.
46.00	-127.00	.	.	.	.	.	.	.	.	.	.
46.00	-126.00	.	.	.	.	.	.	.	.	.	.
46.00	-125.00	.	.	.	.	.	.	.	.	.	.
47.00	-129.00	.	.	.	.	.	.	.	.	.	.
47.00	-128.00	.	.	.	.	.	.	.	.	.	.
47.00	-127.00	.	.	.	.	.	.	.	.	.	.
47.00	-126.00	.	.	.	.	.	.	.	.	.	.

Current state of prediction.

As on July 1, 1992, all the TIP's that are currently active in the western United States have been confirmed by strong earthquakes. These are the Loma Prieta, 1989 and the Landers earthquakes in case of $M_0 = 7.0$, and the last one in case of $M_0 = 7.5$. Until recently in applications of the M8 algorithm we used a kind of external rule which terminates a TIP after a strong earthquake occurs within it. Thus, according to this rule all the TIP's from Figures 4 and 5 would be terminated by now. However, in the global Test of M8 (Healy et al., 1992) we rejected this rule on the basis of the following statistics:

According to the NEIC Data Base during this century there were 322 earthquakes of magnitude $M \geq 7.5$ in the circles of investigation that cover most of the Pacific Rim. 29 of them were accompanied, within 250 km vicinity, by another earthquake from the same population during the first semi-annual, 42 during the first year, 59 during 2 years, and 105 during 4 years.

Another statistical analysis of clustering of major earthquakes can be found in (Kagan, Knopoff, 1976).

On the other hand, the "local" statistics of $M \geq 7.5$ earthquakes suggest that the western United States might be an exclusion from the "global" rule. Being compared to other segments of the Pacific Rim, the region is the one with relatively low seismic intensity: an annual average intensity of a magnitude 6.5 earthquake in a 427 km circle here is 0.175; the eight circles are at the bottom 1/8 of the intensity list of 147 circles from (Healy et al., 1992). Moreover, in his Remarks on the a priori probability of major earthquakes in California and Nevada W.L. Ellsworth presented to NEPEC the summary of all $M > 7.25$ earthquakes here in the last two centuries (Updike, 1989). According to these summary there was no evidence of above-mentioned pairing: the shortest interevent time is about 9.5 years - between the April 18, 1906 California earthquake of $M = 8.25$ and the October 3, 1915 Pleasant Valley, Nevada earthquake of $M = 7.75$.

Thus, there is a dilemma - whether to rely on "local" statistics and cancel all the TIP's or to follow the rules of the Test of M8 and keep the TIP's in Figures 4 and 5.

The TIP's reported in advance.

The predictions for California and Nevada were discussed at a special Meeting of the U.S. National Earthquake Prediction Evaluation Council on June 6-7, 1988. The proceedings of this Meeting are published in (Updike, 1989). Three predictions were reported: a) for M_0 = 6.4 made by algorithm CN ; b) for M_0 = 7.0; and c) for M_0 = 7.5 the last two by algorithm M8.

The first two predictions were confirmed by subsequent Loma Prieta, 1989 earthquake (Keilis-Borok et al., 1990). In the third prediction, for a magnitude $M \geq 7.5$, earthquake the TIP was diagnosed first for the period up to July 1, 1992 in the circle centered at 37.5°N, 119.5°W (it was reported in Keilis-Borok, Kossobokov, 1988, 1990). In preparation to the NEPEC Meeting, in order to outline more precisely the territory covered by the alarm, the additional 24 circles were considered. The centers of these circles and the results of the diagnosis updated through the end of 1987 are shown in Figure on page 8 of the Appendix A in (Updike, 1989). Altogether the TIP's cover the seismic region in between latitudes from 30.6°N to 42.8°N, which is about a half of the whole territory considered. The location of the Landers earthquake falls within this area.

The prediction for California and Nevada can be found also in Healy et al., 1992. As it was already mentioned, this paper describes the design of a rigid test of the M8 algorithm in the Pacific Rim and presents the TIP's diagnosed on the basis of the NEIC global catalog through the end of 1991. The 147 overlapping circles considered were spaced along the Pacific Rim at distances of about 300-400 km between neighboring centers. Such a rarified set of circles have been chosen to make plausible the simple null-hypothesis which require independent diagnosis in the neighbors. Eight circles were placed in the western United States, and the TIP was diagnosed in one of them, centered at 37.5°N, 122°W. This TIP ended on July 1, 1992. The Landers earthquake is about two hundred km off this circle, and therefore is missed in the Test of M8. According to the update of the Test of M8 on July 1, 1992, no current TIP's remain in these eight circles.

Afterword.

The case history of the prediction of an earthquake with $M \geq 7.5$ started in 1985 (Adelman, 1989; Kerr, 1989). A successful prediction of the Loma Prieta, 1989, $M = 7.1$, earthquake should be also mentioned in this context (Keilis-Borok et al., 1990).

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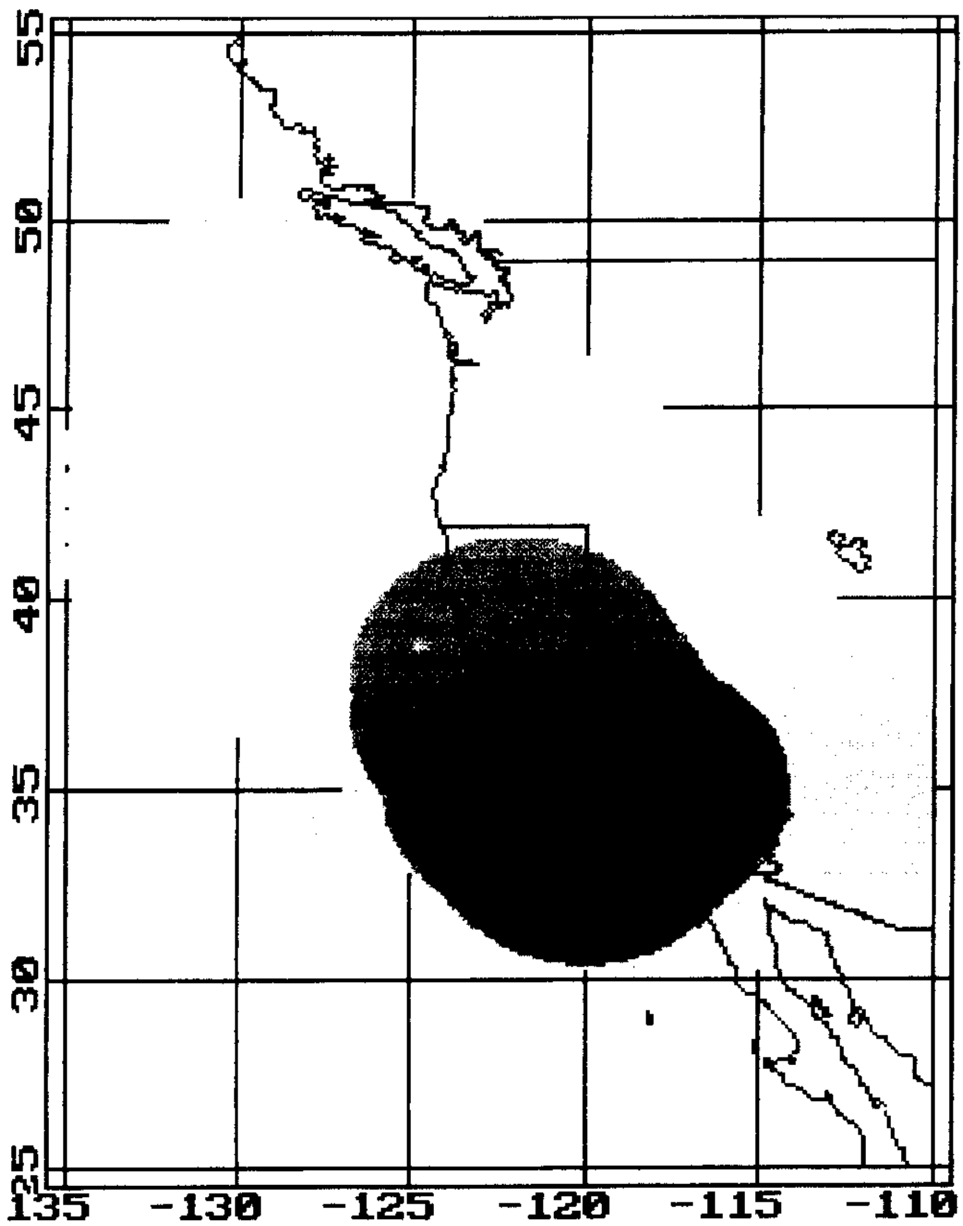
Area of Analysis

The M8 algorithm compiled to predict M ≥ 7.5.

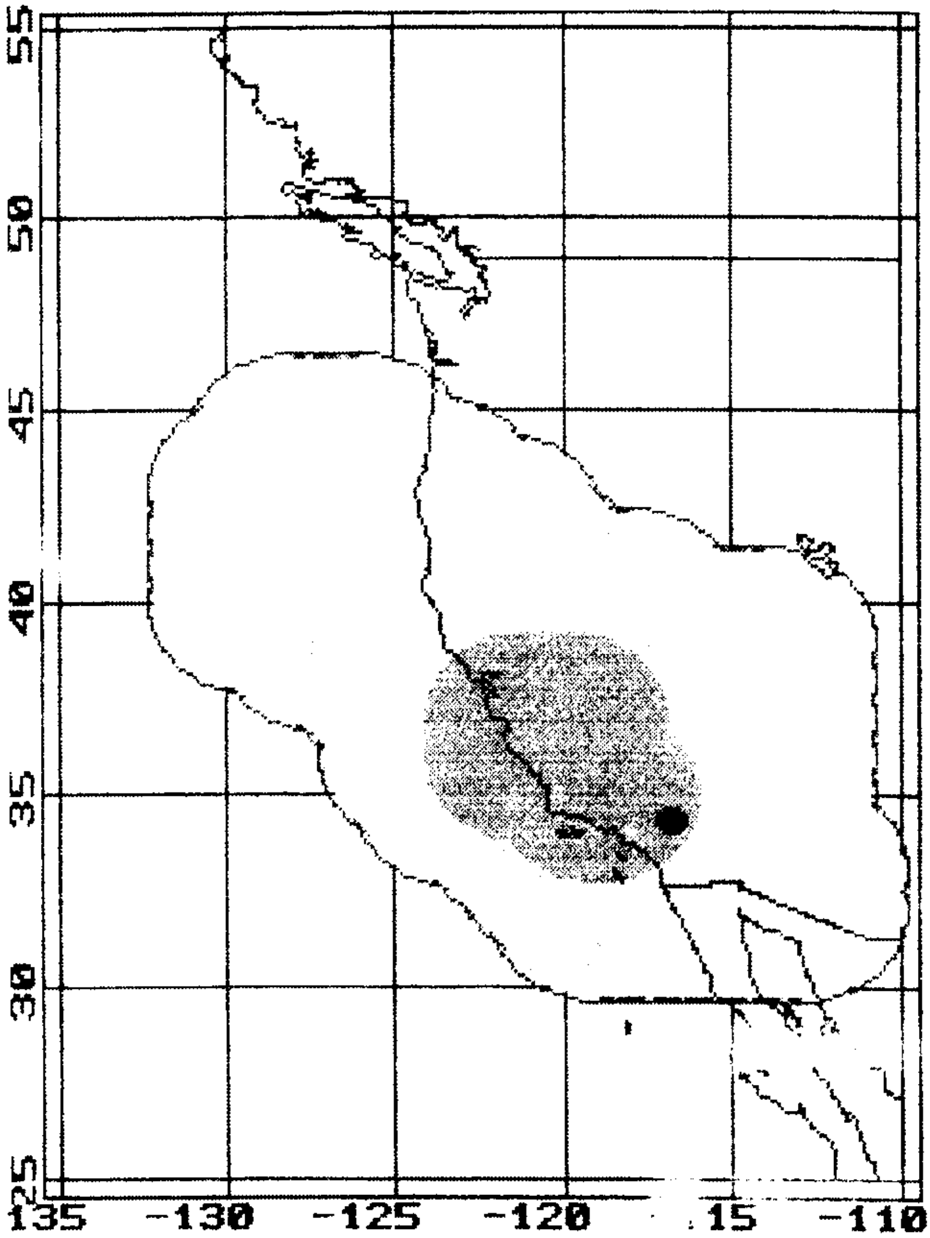


Shaded area outlines the TIP's as on January 1, 1992.
Darker area outlines the TIP's as on July 1, 1992.
Solid Dot indicates the Landers earthquake.

Figure 4.

Area of Analysis

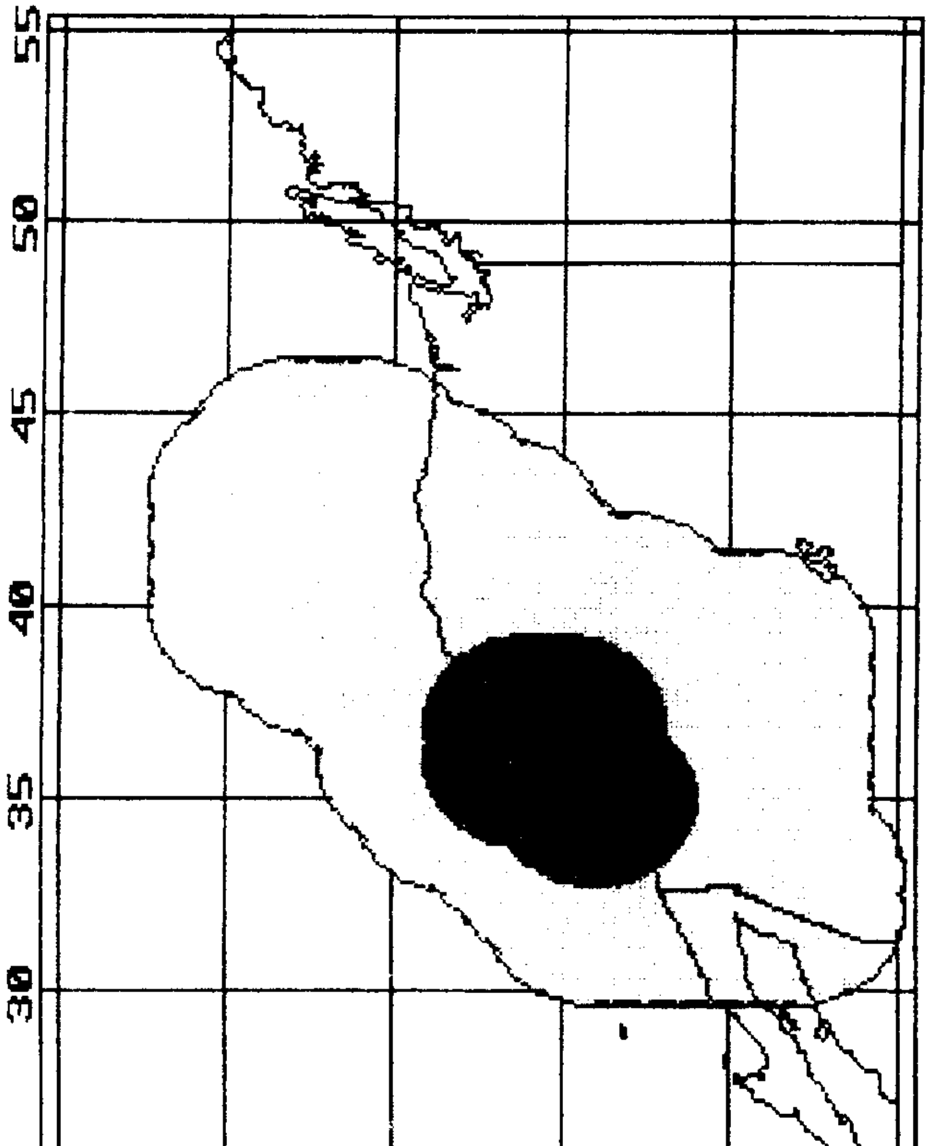
The M8 algorithm compiled to predict M $\geq$ 7.0



Shaded area outlines the TIP's
as on January 1 and July 1, 1992.
Solid Dot indicates the Landers earthquake.

Area of Analysis

The M8 algorithm compiled to predict M ≥ 7.0



Shaded area outlines the TIP's
as on January 1 and July 1, 1992.
Solid Dot indicates the Landers earthquake.

Figure 5.