The forecasting of the 1995 Colima-Jalisco, Mexico, earthquake ($M_w = 8$): A case history

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RESUMEN

En 1995 la región de Colima-Jalisco (103.7-106°W) fue identificada como una zona con una alta probabilidad para la ocurrencia de un gran sismo ($M_s \geq 7.5$) antes de finalizar el año 1996. Este pronóstico se basó en resultados obtenidos del método de reconocimiento de patrones y de estudios de brecha sísmica y la distribución Weibull para la recurrencia de grandes temblores a lo largo de la zona de subducción mexicana. El 9 de octubre de 1995, un evento de magnitud $M_w = 8$ ocurrió dentro del área pronosticada. Un examen detallado de la sismicidad que precedió este sismo revela que la mayoría de los temblores moderados ($M_s \geq 5.5$) ocurrieron fuera del área de ruptura. Estos eventos fueron localizados hacia la costa o hacia la trinchera. El patrón de sismicidad cambió después del terremoto de 1985 ($M_s = 8.1$) el cual ocurrió al sureste, pero no adyacente a la ruptura de 1995. El diagnóstico de este evento pudo haber sido el resultado de una combinación de cambios del patrón de sismicidad seguido de quietud sísmica. Este pronóstico sugiere la importancia de estudios detallados de la sismicidad histórica junto con métodos de reconocimiento de patrones para determinar aquellas áreas con una alta probabilidad de ocurrencia de grandes sismos dentro de un intervalo de tiempo específico.

PALABRAS CLAVE: Pronóstico sísmico, reconocimiento de patrones sísmicos, sismo de Colima-Jalisco, 1995, predicción sísmica, Algoritmo M8.

ABSTRACT

In 1995 the Colima-Jalisco region (103.7-106°W) was identified as a zone with a high probability of occurrence of a large earthquake ($M_s \geq 7.5$) before the end of 1996. This forecast was based on results from pattern recognition and from studies on seismic gaps and Weibull distribution for the recurrence of strong earthquakes along the Mexican subduction zone. On October 9, 1995, an event of magnitude $M_w = 8$ occurred within the forecast area. A detailed examination of the seismicity preceding the mainshock reveals that most moderate earthquakes ($M_s \geq 5.5$) occurred outside the rupture area. They were located mostly onshore or trenchward. This seismicity pattern changed after the great Michoacan 1985 earthquake ($M_s = 8.1$) which took place to the southeast but not adjacent to the 1995 rupture. The diagnosed event may have been the result of a combination of change in seismicity pattern followed by quiescence. The forecasting of this mainshock suggests the importance of detailed studies of historical seismicity together with methods of pattern recognition to determine areas with a high probability for the occurrence of a large earthquake within a specified time interval.

KEY WORDS: Earthquake forecast, seismic pattern recognition, Colima-Jalisco, 1995 earthquake, earthquake prediction, Algorithm M8.

INTRODUCTION

Novelo-Casanova and Álvarez Moctezuma (1995; hereafter Paper 1) pointed out that the western Colima gap and the Jalisco region (103.7-106°W) had a high probability for the occurrence of a large earthquake ($M_s \geq 7.5$) before the end of 1996. The work was based on the identification of times of increased probability (TIP) of strong events and on results from analysis of the historical seismicity and conditional probabilities for the recurrence of large earthquakes ($M_s \geq 7.5$) along the Mexican subduction zone (Nishenko and Singh, 1987). A TIP refers to a five-year period within which a strong earthquake has a high probability of occur-

rence. When a strong event occurs during a TIP, it is indicated as a successful prediction, otherwise it is indicated as failure-to-predict. If no strong earthquake occurs during a declared TIP, the TIP is called a false alarm.

On October 9, 1995 a large earthquake struck the coast of the states of Colima and Jalisco region and caused extensive damage to the city of Manzanillo and coastal towns of both states (Pacheco *et al.*, 1997). Many small fishing villages along the coast were affected by the tsunami that followed, which reached a runup height between two and five meters (Corboulex *et al.*, 1997). Shaking was perceptible in Mexico City located about 600 km from the epicenter. This

earthquake was the largest to occur in Mexico since the great 1985 Michoacán earthquake. The rupture initiated about 20 km offshore of Manzanillo and propagated almost unilaterally for 150 km towards N70°W, with an average rupture velocity of approximately 2.8 km/s (Courboulex *et al.*, 1997). The maximum dimension of the aftershock area was about 170 km x 70 km, oriented N50°W (Pacheco *et al.*, 1997).

The Colima-Jalisco earthquake was located within the forecasted region and it occurred before 1996 as predicted in Paper 1. According to the USGS/NEIC Hypocenter Database, this earthquake had the following magnitudes: m_b= 6.6, M_s=7.4, and M_w = 8.0. Although the value of M_s is 0.1 degree less than the threshold value of 7.5 stated in the prediction, the dimensions of the earthquake rupture and aftershock area allow claiming a confirmation of the prediction in question.

In Paper 1, the 1995 Colima-Jalisco earthquake was forecast within specified coordinates. Most earthquake prediction studies provide a time interval, an area and a magnitude in general terms (Knopoff *et al.*, 1996; Shebalin *et al.*, 2000). Here, we analyze the patterns of seismicity preceding the mainshock to determine the most probable factors that were important in issuing the TIP. A detailed description of the methodology used for the forecast is presented in Paper 1.

SEISMICITY OF THE COLIMA-JALISCO REGION

Large earthquakes in the eastern Colima area (103.0-103.7°W) occurred in 1941 (M_s = 7.9) and 1973 (M_s = 7.5; Singh *et al.*, 1985). Body waveforms for the 1973 event indicate a complex mode of rupture (Chael and Stewart, 1982). Singh *et al.* (1985) defined the western Colima gap between coordinates 103.7 and 104.5°W. This gap was partially filled by the 21 January, 2003, Colima event (M_s = 7.6; Singh *et al.*, 2003).

The Jalisco region (104.5-106.0°W) has generated some large and great earthquakes during last century. Strong earthquakes occurred in 1900 (M_s = 7.6) and in 1932 (M_s = 8.2 and M_s = 7.8). The locations and recurrence periods of large and great earthquakes in this region are uncertain because it is difficult to distinguish between sources in Colima and Jalisco during the nineteenth century (Nishenko and Singh, 1987).

In the Colima-Jalisco region, the Rivera and Cocos plate are subducting beneath the North American plate. To date, the boundary between the Cocos and Rivera plates remains uncertain. Because of the tectonic complexity of the area, it is not clear whether the 1995 earthquake is re-

lated to the subduction of the Rivera and/or the Cocos plate beneath North America (Pacheco *et al.*, 1997).

HOW THE 1995 COLIMA-JALISCO EARTHQUAKE WAS DIAGNOSED

As an approach to intermediate-term prediction, Paper 1 used the M8 algorithm based on the space-time variation of seismicity (Keilis-Borok and Kossobokov, 1986; 1990). The area along the Mexican subduction zone was covered with overlap by three diagnostic circles with diameters (L) of about 7.7° and centers at 13.5°N, 94.5°W (Region 1, Chiapas-Eastern Oaxaca); 14.5°N, 100.5°W (Region 2, Western Oaxaca-Guerrero); 16.5°N, 105.0°W (Region 3, Michoacán-Colima-Jalisco) (Figure 1). These circles were selected to provide coverage of the Mexican Pacific coast. They were not selected to match tectonic structures, or the locations of known major events. Thus, TIPs are likely to be triggered by different factors in different regions.

The 1995 Colima-Jalisco earthquake was diagnosed not only by applying the M8 algorithm but also by using additional criteria of seismic gaps (Nishenko and Singh, 1987). In most M8 studies, the areas identified for the occurrence of large earthquakes were large and the probability of forecasting an event by chance was high (Keilis-Borok and Kossobokov, 1986, 1990). On the other hand, in most seismic gap studies the probable region and size of the earthquake were selected without providing the time interval for the forecast earthquake (Kelleher *et al.*, 1973; McCann *et al.*, 1979; McNally, 1981; Singh *et al.*, 1981; 1982). When a probability of occurrence was provided, the statistical significance of the forecast was too low to be useful (Nishenko and Singh, 1987).

The M8 algorithm is an effective forecasting procedure based on searching catalogues of past events, to identify patterns which occur most frequently before the events which it is designed to forecast. The M8 algorithm incorporates a series of indicator time series, which, together with appropriate threshold values, identify periods of heightened activity and consequently of increased risk. When the threshold values are jointly exceeded, the algorithm announces a TIP for the region under investigation (Keilis-Borok and Kossobokov, 1990). Kossobokov and Shebalin (2003) applied M8 in a global test aimed at seismic events of magnitude greater or equal to 8.0 and the percentage of alarm, estimated by the most conservative measure that accounts for the empirical distribution of epicenters, is about 30% in the Circumpacific. This value is significant as a first approximation prediction and it was enough to prove statistically the significance of prediction by M8 at 99% confidence level.

In Paper 1, algorithm M8 was applied using the standard parameters described by Keilis Borok and Kossobokov

(1986). The National Oceanic and Atmospheric Administration (NOAA-USA) seismic catalog for the period 1961-1991 was used as source data to identify TIPs in the time interval 1970-1991, during which five events of magnitude $M_s \geq 7.5$ occurred along the Pacific coast of Mexico. The analyzed period was selected considering that M8 requires at least 12 years of the seismic catalog to stabilize. The lower magnitude cutoff was 5.5 because the NOAA data base is complete and uniform for earthquakes of this magnitude or larger along the Mexican subduction zone (Habermann, 1988).

Algorithm M8 diagnosed the 1979 ($M_s = 7.6$) and 1985 ($M_s = 8.1$ and $M_s = 7.6$) events. However, the 1973 ($M_s = 7.5$) and 1978 ($M_s = 7.8$) earthquakes were not preceded by a TIP; these were failure-to-predict cases. No false alarms were observed. A TIP was diagnosed only for Region 3.

To test the stability of the diagnosed TIP in Region 3, Paper 1 moved the initial center of the diagnostic circle towards the continent in half-degree steps. In all cases, a TIP was identified. These observations implied that the precise position of the diagnostic circles as well as the standard procedures of the M8 algorithm were not critical to the results. Once the TIP was confirmed, Paper 1 stated:

"We consider that there is a strong possibility that the observed TIP may correspond to the area between 103.7 and 106.0°W for two reasons: (1) the Western Colima gap identified between coordinates 103.7 and 104.5°W has not experienced a major shock during the last 90 years (Singh *et al.*, 1985); (2) for the 104.5-106.0°W segment, owing to the lack of precision on the probability estimates for large shocks in this area, a recurrence time for great earthquakes has been difficult to estimate (Nishenko and Singh, 1987)… These observations may indicate that somewhere in the Colima-Jalisco region … sufficient energy is being accumulated to be released in a major earthquake in the near future (before 1996)…".

SEISMICITY BEHAVIOUR BEFORE THE 1995 COLIMA-JALISCO EARTHQUAKE AND DISCUSSION

Figure 1 shows the epicenter and the aftershock area of the 1995 Colima-Jalisco earthquake as determined by a local network (Pacheco *et al.*, 1997). Also, the segment for which the earthquake was forecast is displayed. Note that the rupture is completely within the forecast interval in Region 3.
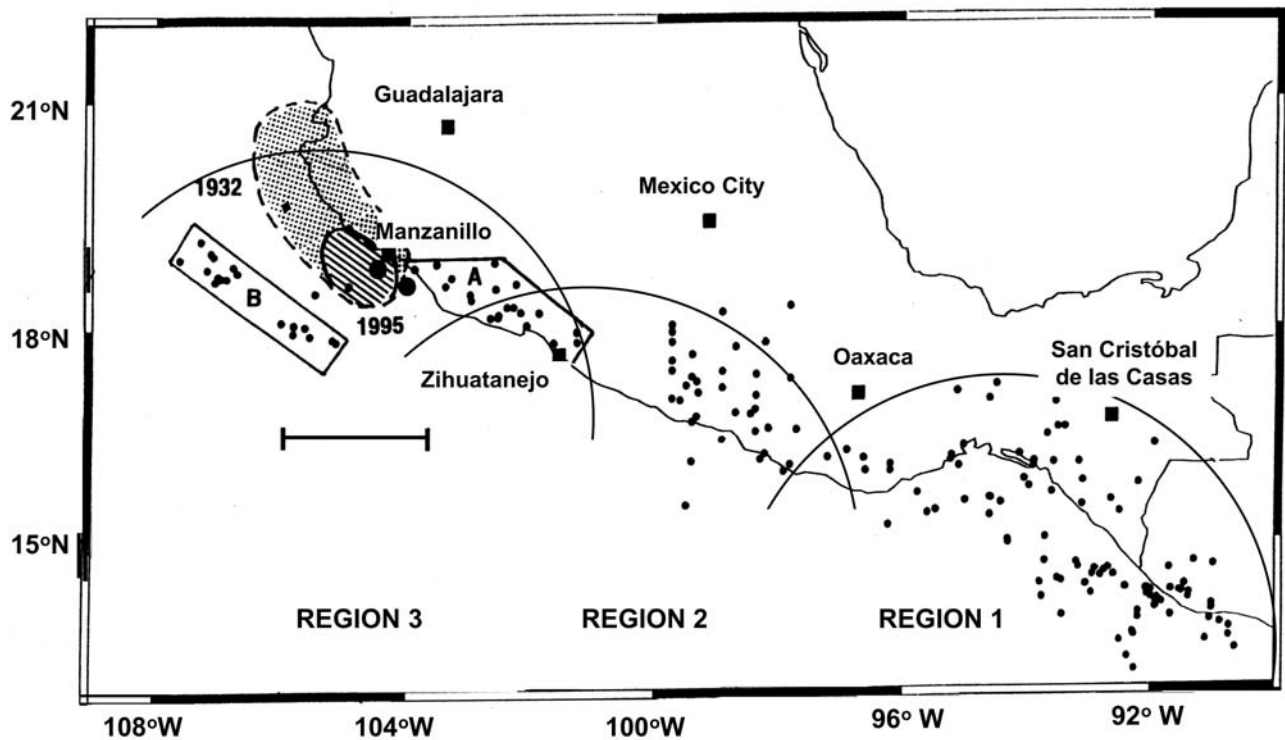

Fig. 1.Epicenters of earthquakes with $Ms \geq 5.5$ for the time interval from 1961 to 1991 (small solid dots) and portion of the diagnostic circles analyzed in Novelo-Casanova and Álvarez-Moctezuma (1995). The large solid dot and the hachured zone indicate the epicenter and the aftershock area of the October 9, 1995 event determined by a local array (Pacheco *et al.*, 1997). The shaded zone outlines the rupture region of the great 1932 Jalisco earthquake (Singh *et al.*, 1985). The horizontal interval in Region 3 represents the segment for which an earthquake of $M_s \geq 7.5$ was forecast to occur before the end of 1996 (Novelo-Casanova and Álvarez-Moctezuma, 1995). Zones A and B outline regions of seismic activity concentration.

Considering that a TIP arises as result of the appearance of a certain combination of patterns of seismicity before large earthquakes, we analyzed in detail the space-time epicentral distribution of the background seismicity for events with $M_s > 5.5$ that occurred in Region 3 for the period from 1961 to 1991 (Figure 1).

Region 3 displays a zone almost devoid of earthquakes surrounded by two areas of seismic activity concentration (Figure 1). One of these areas is located along the coast line within the continent and between Zihuatanejo and Manzanillo (Zone A). The other area with concentration of earthquakes is located towards the ocean at about 200 km from the city of Manzanillo (Zone B). Figure 2 displays the earthquake distribution in Region 3 at five-year intervals and for one period of six years (1986-1991).

From 1961 to 1975 most of the seismic activity was practically concentrated in Zones A and B, to the east and west of the source zone of the Colima-Jalisco earthquake. From 1976 not a single event of $M_s \geq 5.5$ occurred near the rupture area of the mainshock. From 1976 to 1985 only four and two earthquakes occurred in Zones A and B, respectively. For the time interval 1986-1991, however, six events occurred in Zone B. The two earthquakes in Zone A for this last period took place within the first five months of 1986. This
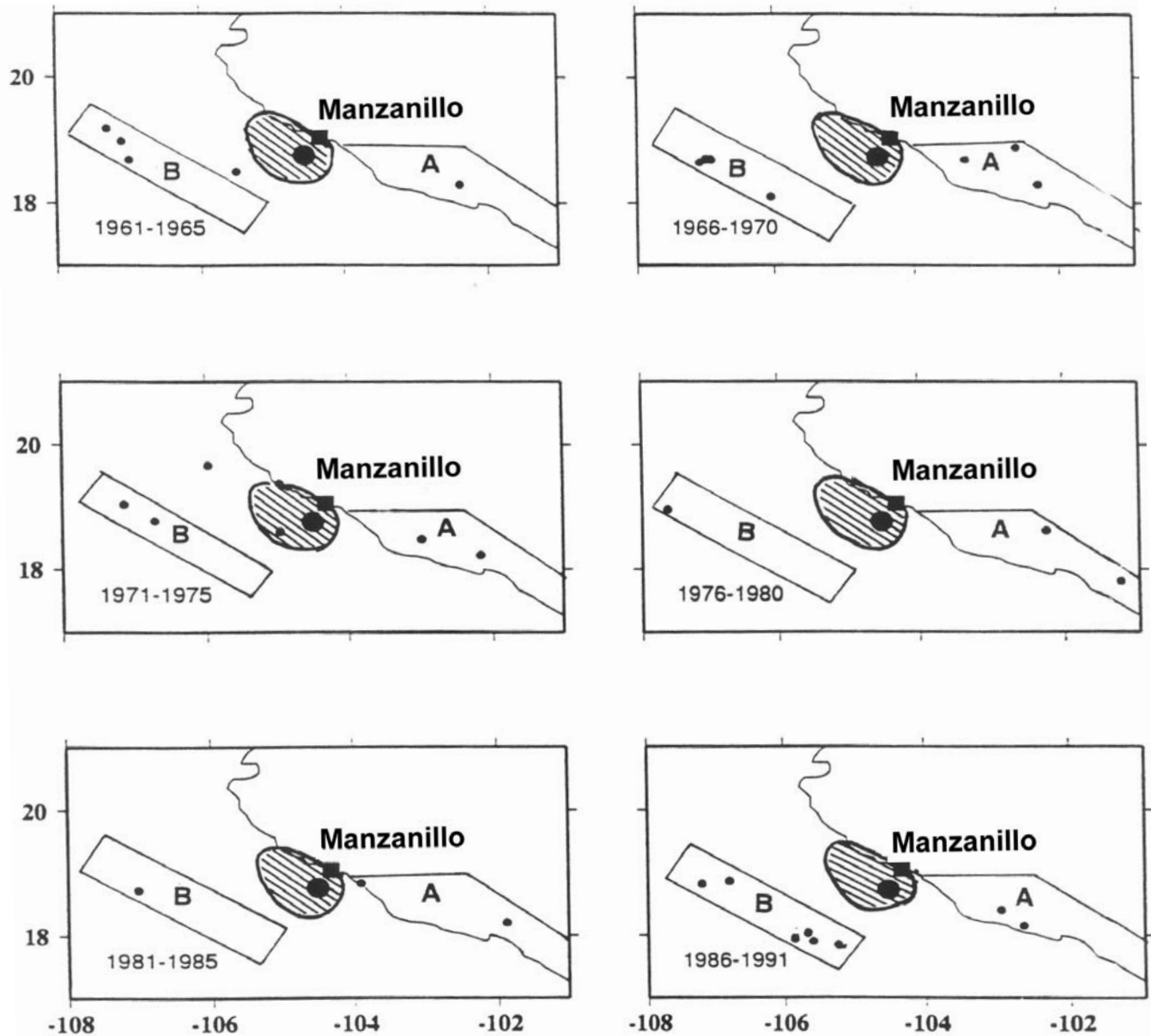

Fig. 2. Temporal and spatial variations of the epicenters located in Region 3 of Figure 1. The large solid dot and hachured region represent the epicenter and aftershock area of the 1995 Colima-Jalisco earthquake, respectively.

implies that Zone B was more active from the end of 1986 up to 1991 (starting ten years before the mainshock). It is important to point out that after 1991 and before the Colima-Jalisco earthquake, no event of $M_s \geq 5.5$ occurred in Region 3, except for the foreshock of October 6, 1995 ($M_w = 5.8$). This space-time distribution of seismicity is shown schematically in Figure 3.

The spatio-temporal patterns and rise of seismicity as well as the earthquake clustering (in Zones A and B) described here were recognized by algorithm M8 for issuing the forecast of the Colima-Jalisco mainshock. Some studies, however, impose no limitations on territorial distribution of precursory activity. The earthquakes forming a premonitory pattern may be either spread over the whole region or concentrated in a small area not necessarily close to the epicenter of an incipient strong earthquake (Knopoff *et al*., 1996; Shaw *et al*., 1997; Bowman *et al*., 1998; Kossobokov *et al*., 1999a, 1999b).

The aftershock area of the mainshock is within the aftershock region of the Jalisco event (Figure 1). Nishenko and Singh (1987) assigned a low conditional probability for the 104.5 106°W segment because they considered a recurrence period T_r to be between 77 and 126 years. Their observation was based on a convergence rate of the Rivera plate of 2 cm/

year. If the Colima-Jalisco earthquake was a repeat of the 1932 event, then T_r should be approximately 63 years and the convergence rate would ride to about 4.8 cm/year. This value agrees with the estimates of the convergence rate of the Rivera-North American plates of Bandy and Pardo (1994).

CONCLUSIONS

The October 9, 1995, Colima-Jalisco earthquake was successfully forecasted in Paper 1. The most important factor in issuing the forecast was the appearance of spatio-temporal patterns of seismicity for earthquakes of moderate magnitude a few years before the mainshock. The seismicity pattern preceding the 1995 earthquake was as follows: most moderate earthquakes during 1961-1985 occurred either onshore to the south of Manzanillo (i.e., on the Cocos North America plate boundary), or offshore and trenchward from the 1995 rupture (Figure 1). Between 1986 and 1991 six events occurred offshore and trenchward from the 1995 rupture zone. After 1991 and before the Colima-Jalisco earthquake, no further event of magnitude 5.5 or above occurred in the region (except the October 6, 1995 foreshock). This pattern of seismic activity was picked up by the M8 algorithm and led to the forecast.

The procedures used in Paper 1 indicate a possibility of further improvement of the intermediate term earthquake predictions in course of case-specific statistical and pattern recognition studies of seismic characteristics in more detail.
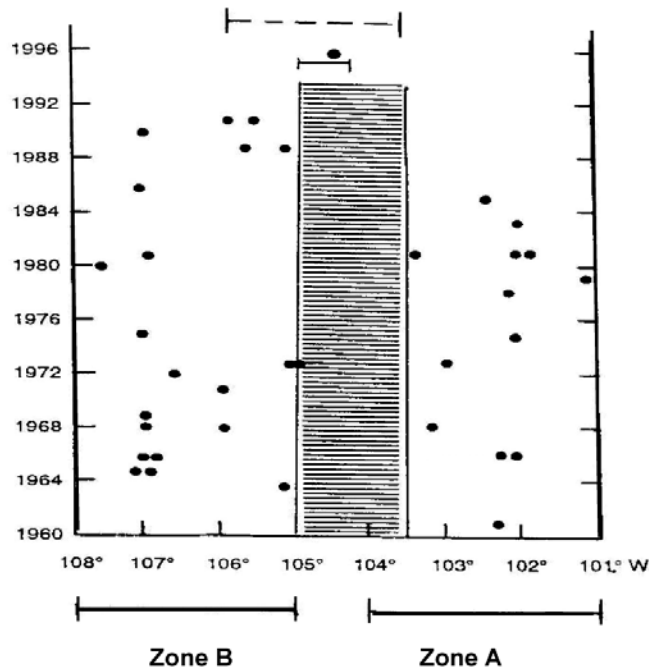
Fig. 3. Space-time diagram of the events shown in Fig. 2. The dot and the horizontal segment in 1995 indicate the location of the October 6, 1995, foreshock and the approximate lateral extent of rupture of the Colima-Jalisco earthquake, respectively. The horizontal dashed line shows the segment for which the earthquake was forecast. Note the lack of seismic activity between coordinates 103.5-105.0°W.

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