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Triggered seismicity in the Valley of Mexico from major Mexican earthquakes

S. K. Singh1, J. G. Anderson2 and Miguel Rodríguez3

1 Instituto de Geofísica, UNAM, C.U., México, D.F.

2 Seismological Laboratory, Mackay School of Mines, University of Nevada, Reno, Nevada.

3 Instituto de Ingeniería, UNAM, C.U., México, D.F.

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RESUMEN

Se hizo un análisis detallado de los boletines y sismogramas registrados en la Ciudad de México desde 1920, para cono-cer si los sismos ocurridos en la zona de subducción a lo largo de la costa del Pacífico mexicano, con Mw>7.0, causaron in-cremento de sismicidad local en el Valle de México. En siete de diez sismos analizados hasta 1957, encontramos incremento en la sismicidad del valle, aun cuando el incremento en uno de estos casos es pequeño. Un modelo estadístico indica que la probabilidad que estos incrementos ocurran por coincidencia no es significante. Para ocho sismos después de 1957 encontramos que los resultados son más ambiguos debido al incremento en el nivel de ruido y a la necesidad de utilizar dife-rentes estaciones sismológicas en el análisis. El incremento en sismicidad local después de los sismos de 1985 es claro, y para los eventos de 1978 y 1979 notamos un incremento pequeño en la actividad. Durante los eventos que fueron seguidos por un incremento en la sismicidad local, las amplitudes de las deformaciones de cortante y de dilatación fueron mayores o iguales a 3 y 2 microdeformación unitaria, respectivamente, mientras que durante aquellos que no causaron incremento, las deformaciones calculadas son menores o iguales a estos valores. Las observaciones presentadas son consistentes con el modelo de disparo de actividad sísmica en el Valle de México. También son consistentes con la existencia de un umbral de deformación, que debe excederse para causar el disparo. El retrazo observado del incremento de sismicidad puede asociarse al proceso de arrastre o al flujo de fluidos.

PALABRAS CLAVE: Sismicidad, Valle de México, efecto de gatillo, disparo.

ABSTRACT

We have made a systematic examination of seismograms and bulletins from Mexico City since 1920 to examine whether major and great subduction zone earthquakes along the Pacific coast of Mexico caused increases of local seismicity in the Valley of Mexico, which is situated in the Trans Mexican Volcanic Belt. Of ten coastal events analyzed through 1957, seven events are followed by seismicity increases in the valley, although the increase in one of these cases is small. The probability that these increases occur by coincidence is negligible. Eight large coastal earthquakes since 1957 were also examined. For these events the results are more ambiguous due to an increase in the cultural noise and the necessity to use different seismic stations. It is clear, however, that the two 1985 earthquakes were followed by an increase in local events. A small increase in the activity is noted following events in 1978 and 1979. During the events which were followed by increased activity, the computed shear strain amplitudes and dilatations were greater than or equal to 3 and 2 microstrains, respectively, while for the events that caused no increase in seismicity, the computed strains were less than or equal to these values. These observations are consistent with the possibility that the activity in the Valley of Mexico was triggered. They are further consistent with the existence of some threshold in strain that needs to be exceeded to cause remote triggering of earthquakes. The observed delays in the triggered seismicity could be caused by either creep or fluid flow processes.

KEY WORDS: Seismicity, Valley of Mexico, triggered seismicity.

INTRODUCTION

The discovery that the Landers earthquake may have triggered small events at relatively large distances (Hill *et al*, 1993; Anderson *et al*, 1994; Bodin and Gomberg, 1994; Gomberg and Bodin, 1994) has stimulated investigation of the causal mechanism, and raised the question of how often this phenomenon occurs. In this paper we report on potentially triggered seismicity in the Valley of Mexico, as related to the sequence of large earthquakes along the subduction thrust beneath the Pacific coast of southern Mexico. The study is possible because sensitive seismographs have been operating continuously in the Valley of Mexico since 1909.

Hill *et al.* (1993) proposed that the triggering after the Landers earthquake occurred in areas of volcanic or hydrothermal activity. The Valley of Mexico is located in an area of both volcanic and hydrothermal activity. The southern part of the valley was flooded by a basaltic lava eruption in historical times (about 3000 years ago). Popocatépetl, an active volcano, lies about 50 km east-southeast of Mexico City. There are old reports of geothermal activity in the valley, although this has recently decreased because of increased mining of ground water in the latter half of the 20th century.

At its nearest approach, the subduction thrust is 250 km from the Valley of Mexico (Figure 1). Large/great earthquakes occur both along the interplate boundary as well as within the subducted Cocos plate. The three largest thrust events of this century are the June 3,1932

Jalisco earthquake (M_s=8.2, Δ=578 km), the September 19, 1985 Michoacán earthquake (Mw = 8.0, Δ = 397 km), and the Colima-Jalisco earthquake of October 9, 1995 (Mw = 8.0; Δ = 562 km). Knowledge that the 1932 and 1985 earthquakes were followed by local events in the Valley of Mexico, far outside the aftershock zone, suggested a more systematic search in earlier records. Mexico City newspapers reported extensive local seismicity just before and after the 1932 earthquake. Following the 1985 event there were reports of felt earthquakes which could be verified from the seismograms.

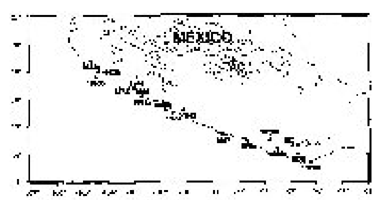

Fig. 1. Map showing epicenters of events analyzed and the seismic observatory of Tacubaya (TAC), which is located in the Valley of Mexico. Shaded area represents the Trans-Mexican Volcanic Belt.

Figure 2 shows a map of Mexico City and the surrounding region. This figure includes epicenters of earthquakes that have been located in the time interval 1993 to 1995, locations of seismographic stations used in this study, and an indication of the present extent of the urban area. Prior to 1993, the seismic network in the Valley of Mexico was sparse, so that small events could not be located. From 1909 until 1974, the only station was at Tacubaya (TAC), which in those times was located west of the urbanized area. Because it was the only station in the area, locations can not be determined, but local events can be recognized on the seismograms by short S-P times. In the 1950's, the urban area spread around Tacubaya, and the station became increasingly noisy. In 1974, a new local station was installed on the campus of the Universidad Nacional Autónoma de México (UNAM). With continued growth of Mexico City, the cultural noise at that station has also increased, so the detection threshold of events there has diminished. At present, there are several seismic stations in the hill zone of the Valley of Mexico, and several stations surrounding Popocatépetl volcano. Recognition of quarry blasts becomes increasingly important also as Mexico City has grown. We are reasonably confident, however, that the epicenters in Figure 2 are all earthquakes.

Looking at Figure 2, one gets the impression that there are relatively few local earthquakes near TAC and UNAM. However, considering the difficulties of locating earthquakes in this region, this shortage could easily be an artifact. Small events occurring very close to either TAC or UNAM would not show up in this catalog. Thus the figure shows a diffused band of seismicity in the Valley of the Mexico. Two recent events in the valley, both with local magnitude 3.9, have been studied by UNAM and CENAPRED Seismology Group (1995). Both events had normal-left oblique faulting mechanisms on roughly northwest-southeast striking planes. The sense of slip is such that the Valley of Mexico is on the subsiding block.

We limited the scope of this study to seven time intervals (Table 1). Major earthquakes during these intervals are listed in Table 2. Figure 1 shows the epicenters of these large earthquakes. Several large earthquakes occurred in Oaxaca in 1928 and one in 1931, and two large earthquakes occurred in Jalisco in 1932 (Table 2). The quiet interval between 1920 and 1927, in which no large events occurred in Mexico, was used to develop a background seismicity level. The other intervals (Table 1) include the most damaging earthquakes to the Valley of Mexico, and thus are likely to be associated with the strongest shaking. They also include the three largest earthquakes with magnitude Mw=8.0. Without increasing the workload to unmanagable levels, these intervals include most of the significant seismic activity.

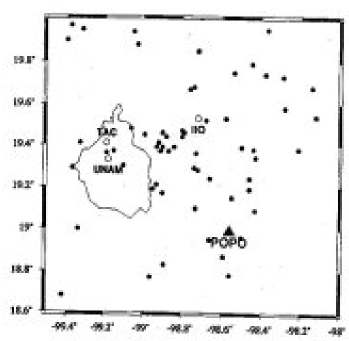

Fig. 2. Map of the Valley of Mexico region. Mexico City is shown by the contour. Seismic stations mentioned in the text, TAC, UNAM, and IIO, are shown by open circles. Popocatépetl (POPO), an active volcano, is indicated by a solid triangle. Dots are epicenters of locatable earthquakes from 1993-1995.

Table 1

Time Intervals Examined

For events up to 1973, we analyzed seismograms from the Wiechert 17-ton horizontal seismograph located in Tacubaya (TAC). This instrument has a static magnification of 2000 and a natural period of 1.5 sec.

Seismograms were only saved at TAC if the observer decided that there was a significant earthquake on the seismogram. The bulletins include detailed descriptions of earthquakes seen on the seismogram and the observers were very conscientious in sorting the records. For time intervals 4 to 7 we could examine daily seismograms as none were discarded. We checked all available seismograms for the period from 1920 to 1934, and for intervals 2 to 7. For all local events, we measured coda duration and amplitude (although amplitude was eventually not used). A local event was defined to be any event with S-P time of less than 8 sec, but most S-P times are under 3.0 sec. For time intervals 1 and 2, a cross check of the bulletins and the saved seismograms suggests that our catalog is complete for local events of coda duration greater than 60 sec. For events with duration $\geq$ 60 sec, there is little difference in representing the seismicity by the amount of moment release or by the number of events. In this study we have used the moment release as a measure of seismicity. As there is no study to relate magnitude and seismic moment to coda duration, specifically for local events in the Valley of Mexico as recorded on TAC or local high-gain stations, we used the relation $Mc = 2.0 \log T - 0.87$, where T is coda duration in seconds, from Lee *et al.* (1972), to convert coda duration to magnitude. To obtain seismic moment, Mo, in dyne-cm, we used the relationship from Hanks and Kanamori (1979): $\log Mo = 1.5 Mc + 16.0$. Regionally derived relationships would probably differ slightly in constants, but would not affect our results.

Figueroa (1971) estimated the annual frequency of seismic events in the valley between 1909 and 1969, and found a ten-fold increase in the last twelve years of the interval. Alberro and Hernández (1991) suggested a correlation between this seismicity and annual rainfall recorded at Tacubaya. Our examination of seismograms from this period suggests that most of the events reported by Figueroa for the latter years are actually of cultural origin, with coda lengths of five seconds or less.

For time interval 4, TAC, the only station operating in the valley, is affected by severe cultural noise. For intervals 5 and 6 (Table 1) we substituted the station UNAM for TAC. This introduces some ambiguity because of site and instrumental differences between UNAM and TAC. For time interval 7, the cultural noise at UNAM was also too severe for the records to be useful. Thus we looked at records from station IIO (Figure 2). However, the relatively well-controlled experimental conditions that characterize the data up to 1957 are no longer present in later years.

Results

In Figure 3 we present a histogram showing the annual seismic moment released for the years 1920-1934. The average moment release for 1920 through 1927 is about 600x1018 dyne-cm/yr. In this figure, there are two significant clusters of activity in the Valley of Mexico: one in 1928 and the other in 1931-1934. On this scale, these clusters of activity correlate with the large earthquakes on the coast, as indicated on the figure.

Figures 4 and 5 show a series of histograms of monthly and daily activity rates, at times surrounding some of the large earthquakes on the coast. Figure 4 is on a scale that only allows recognition of general patterns, which show some correlation between large seismic moment release by local events and the occurrence of large coastal earthquakes. To investigate the temporal relationships between earthquakes on the coast and the Valley of Mexico in more detail, Figure 5 shows daily moment release from local seismic activity.

Table 2

Major (M≥7) Seismic Events During Time Intervals Studied1

1 Locations and depths from Courboulex *et al.*, (1997a, b) for earthquakes of 1995 and from Singh and Mortera (1991) and Singh *et al.* (1985) for earlier events; Mo and Mw from Harvard CMT catalog for events of 1995 and from Anderson *et al*. (1989) for earlier events.

2 Azimuth of TAC from the epicenter.

3 Legend for symbols:

□ Earthquakes follow within 2 days

O Earthquakes follow, but delayed up to one month

* Preceding earthquakes

? Ambiguous, see text

x No associated earthquakes

Figure 4a presents monthly activity for the period 1920-1927 and Figure 4b shows the monthly activity between 1928 and 1931. Figure 5a investigates the interval of July through December 1928 more closely. The March 22, 1928 earthquake was not associated with any significant activity in the Valley of Mexico. Although the monthly June activity was about the same as in January, there was a sharp increase in the number of events immediately after the June 17 earthquake. In the 30 days after June 17, we estimate the moment release was about 850x1018 dyne-cm, 17 times the average for 1920 to 1927. After the August 4 event, there is no immediate increase in either number or moment of events, but there is a delayed increase and the moment release in the subsequent 30 days is 3800x1018 dyne-cm. The October event is followed by an immediate increase in number of events and the 30-day total is about 2900x1018 dyne-cm. It is interesting to note that after both the August and October events the times of largest moment release in the Valley of Mexico are delayed.

As is seen in Figure 3, the 1932 sequence of local earthquakes is by far the most significant in the 1920-1934 time interval. Based on other accounts, there is no comparable sequence in the known history of the Valley of Mexico (Figueroa, 1971). A monthly account of the 1932-1933 activity is shown in Figure 4c, and a daily account in Figure 5b. On the monthly scale, the 1932 peak corresponds approximately to the time of the Jalisco earthquakes, although the peak in May precedes the events. The 1933 strain release is caused by a single event in August, and probably has no particular significance.

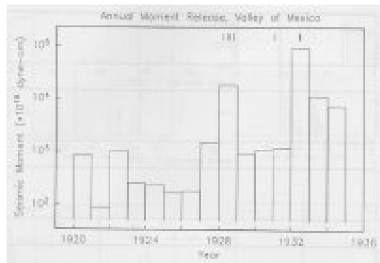

Fig. 3. Histogram of annual moment release in the Valley of Mexico for the years 1920-1934. Vertical bars show times of large earthquakes.

Figure 5b shows that the largest moment release preceded the June 3 main shock by 5 days. Within 48 hours, the activity had decreased essentially to zero, so that June 1 and June 2 records were not kept, and the bulletin indicates no activity. The June 3 seismogram, with the large earthquake from Jalisco, is also missing. June 4 records and the bulletin show that there was renewed local activity, which largely disappeared within 9 days. After the June 18 earthquake, local activity was again renewed, decreasing to unrecorded levels within 9 days. Our estimated moment releases from June 3 to June 18, and 30 days after June 18, are ~ 13,000 and 21,000x1018 dyne-cm, respectively. We consider it likely that the local activity after June 3 was triggered. No locations of any of these local earthquakes are known. Felt reports are widespread, but not specific enough to determine if the June 4 and later events are collocated with the May 28-30 events. There is one difference between the earthquakes before and after the June 3 coastal earthquake. Seismograms from May 29-30 and from June 4 are shown in Figure 6. The seismograms of May 29-30, which represent the local event and its aftershocks, include 'typical' earthquakes with a very weak P-wave, and a large, impulsive S-wave. These records also include events that look much more harmonic. We speculate that the harmonic events have very shallow sources, and that the harmonic waves are surface waves in the lake bed. Among the records that we examined for the time period after the June 3 earthquake, these latter, harmonic waves are not present. Thus the locations of the June events do not entirely overlap the locations of the May events. We consider it possible that both 1932 earthquakes triggered local events in a source area distinct from the May 29-30 sequence. If the source of the June events is the same as the May 29-30 sequence, then at least Figure 5b gives the strong impression that the times of local aftershocks were modified.

Figure 4d shows monthly moment release during the second time interval. There is no triggered seismicity in the valley related to the April 15, 1941 earthquake. There is a peak in the moment release during October 1942, which is not related to any significant earthquake on the coast of Mexico. Although no immediate increase in the seismicity follows the February 22, 1943 earthquake, a relatively large moment release occurs about a month later. This is more clearly seen in the daily moment release shown in Figure 5c. In the 30 days after the event the cumulative moment release was about 2100x1018 dyne-cm.

Figure 5d shows the daily moment release for July-August, 1957. The day after the 1957 event, there appears to be a relatively strong pulse of seismic moment release, with a 30-day cumulative value of 2000 x 1018 dyne-cm.

The TAC seismograms for the fourth interval (Jan-Dec, 1973) are strongly affected by cultural noise. For this reason, it is not possible to know whether the earthquake of Jan 30, 1973 caused any triggered seismicity in the Valley of Mexico.

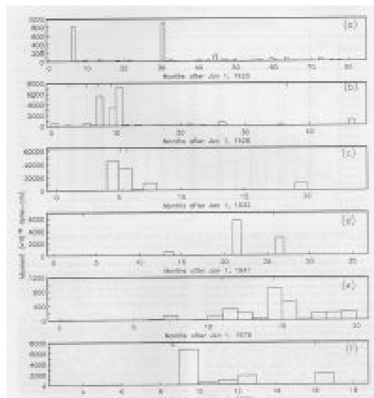

Fig. 4. Monthly histogram of moment release in the Valley of Mexico for several time intervals: (a) January 1920- December 1927; (b) January 1928- December 1931, (c) January 1932- December 1933; (d) January 1941- December 1943; (e) January 1978- August 1979; (f) March, 1985- June, 1986.Vertical bars show times of large earthquakes.

Figure 4e shows monthly activity corresponding to the fifth time interval in 1978-1979. In this case, as mentioned previously, we had to use a different station. Figure 5e breaks the monthly counts down to the daily release for October 1978 to May 1979. A weak increase might have followed the 1978 Oaxaca event.This observation is also consistent with only a small increase in seismicity after the June 1928 Oaxaca earthquake, which is believed to have ruptured the same fault segment (Singh *et al*., 1981). A higher peak in monthly activity at the time of the 1979. Petatlán event (Figure 4e) includes comparable numbers of earthquakes before and after the earthquake. Figure 5e shows that two events of about the same size occurred, one just before and the other just after the coastal event. We consider the evidence for remote triggering following the 1978 Oaxaca and the 1979 Petatlán events to be marginal and ambiguous.

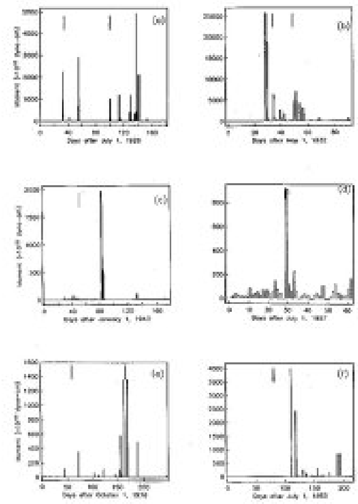

Fig. 5. Daily histogram of moment release in the Valley of Mexico for several time intervals starting: (a) July 1, 1928; (b) May 1, 1932; (c) January 1, 1943; (d) July 1, 1957; (e) October 1, 1978; (f) July 1, 1985. Vertical bars show times of large earthquakes.

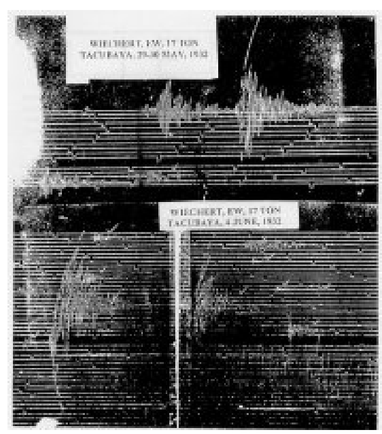

Fig. 6. Samples of Wiechert seismograms from 1932. Top: May 29-30; Bottom: June 4. Note that the great Jalisco earthquake (Mw 8.0) occurred on June 3.

Figure 4f shows monthly activity in 1985. In this case, the main shocks occurred in September, and there is a large peak initiating in October. Finally, Figure 5f shows daily activity around the September 19, 1985 earthquake and its aftershock of September 21. Based on Figure 4f, the rate of activity in the month of October, after the main shock, was unusually high. However, Figure 5f shows that there was a lag of almost a month before the large moment release from the local sequence.

We examined the seismograms from station IIO to study the local seismicity during the last time interval (January-December 1995). This station is about 50 km northeast of TAC and

UNAM (Figure 2). For this reason the seismicity at IIO can not be directly compared with that at TAC and UNAM. We found no clear and overwhelming evidence of triggered seismicity related to the September 14, 1995 event. There is some evidence of an increase in the seismicity about a month after the occurrence of the October 9, 1995 event, but it is not very intense. We conclude that the result from the analysis of the IIO seismograms is inconclusive.

A Statistical Significance Test

An important question is whether the relationship between the observed increased seismicity in the Valley of Mexico and the occurrence of large/great earthquakes in Mexico is statistically significant. For this purpose, we developed a statistical test. The most homogeneous data set available is from January 1, 1920 through December 31, 1934, for a total of 15 years, or 180 months. During this time interval, there are 8 months in which the moment release detected by the Tacubaya station exceeds 1000 x 1018 dyne-cm. The probability, p, of a randomly selected 30-day interval having this much moment release is p = (8/180) = 0.0444. The catalog of large Mexican earthquakes that we are using (Anderson *et al.*, 1989) identifies seven large events in this time interval. We assume that the times of these events are random. Then, we estimate the probability that none, one, two,... up to seven of these randomly chosen time intervals of 30-day duration would have an increased seismic activity in the Valley of Mexico.

For any time interval, increased activity does occur (probability p), or it does not occur (probability q=1-p). The probabilities of the possible outcomes of this experiment then can be described by a binomial distribution. Table 3 lists each term of the distribution. The most likely outcome is that none of the time intervals after large earthquakes would have associated activity in the Valley of Mexico. The outcomes that none, one, or two of the time intervals would have activity cover 99.73% of the cases. The probability that four or more events would have associated activity in the valley is about 1.2x10-4. Thus, the observation that four of the seven events are associated with subsequent activity near Mexico in excess of 1000x1018 dyne-cm has a probability of about 0.01%.

We may carry out the same analysis adding the time interval from January 1, 1941 to December 31, 1943. This adds 36 months of observations, in which 2 months had seismicity in excess of the 1000x1018 dyne-cm threshhold. It also increases the number of events in the catalog by two, of which one is followed by activity in the valley. In this case, following the same steps for the analysis, the probability that 5 or more events could be associated with activity in the Valley of Mexico is smaller than 10-4, so that the conclusion that the activity in the valley is associated with earthquakes on the coast is given even stronger statistical support.

Estimated Strains from Coastal Earthquakes

We summarize our observations in Figure 7 and Table 2. Figure 7 shows the seismic moment released by large events as a function of epicentral distance to Tacubaya. The observations are divided into the following categories: 1. Clearly no seismicity associated with the coastal earthquake (X). 2. Valley of Mexico seismicity that increases immediately (within 2 days) after the coastal earthquake (☐). 3. Seismicity in the Valley of Mexico increases but is delayed by up to about 30 days (o). We also use a special symbol to indicate those coastal events that were preceded by Valley of Mexico earthquakes (*). Several earthquakes have more than one of these characteristics, as shown in Table 2. We note that those coastal events that are followed by high Valley of Mexico seismicity can be approximately separated from those which are not by a linear relationship, which is shown by a dashed line. In this plot there are two inconsistencies: the August 4, 1928 and April 15, 1941 events fall below the dashed line. We note that the two events for which the seismicity increase is ambiguous (the earthquakes of 1978 and 1979) fall above the line.

Anderson *et al.* (1994) suggested that there is a threshold in strain, which depends on the region, so that triggered seismicity will occur when this threshold is exceeded by transient waves from a strong earthquake. The ability to separate earthquakes into two groups on Figure 7 might be evidence in favor that hypothesis. Following Anderson *et al.* (1994), we calculated possible strain seismograms at long periods for most of these events. The only events not considered in this way occurred in 1973 and 1995, for which the Valley of Mexico seismicity is poorly known. The strains were calculated using the velocity model described by UNAM and CENAPRED Seismology Group (1995), which has been calibrated to correctly reproduce long-period ground motions in Mexico City from earthquakes along the coast (Campillo *et al.*, 1996), and to be consistent with local velocity measurements in the shallow crust under Mexico City (Havskov and Singh, 1977-78). Since all coastal earthquakes are at least 300 km from Mexico City, we felt justified in using a point-source approximation to represent the earthquake, convolved with a time function appropriate for each earthquake (Singh and Mortera, 1991). There is little variation in focal mechanisms along the coast (Pardo and Suárez, 1995), so we used a common focal mechanism for all events. The one exception was the normal-faulting Oaxaca earthquake of 1931 for which we took the mechanism given in Singh *et al.* (1995). The strain was calculated for the location of Tacubaya at a depth of 4 km.

Figure 8 shows two types of strain time series, on a greatly compressed time scale: the effective dynamic strain (left) and the dilatation (right). The effective dynamic strain time series are organized into two groups: those with subsequent activity, and those without. Within each group, events are organized according to decreasing levels of effective dynamic strain, which is a scalar quantity representing the shear strain tensor (see Anderson *et al.*, 1994). The interesting feature of Figure 8 is that during earthquakes which caused triggering, threshold levels of the effective dynamic strain of about 3 microstrain, and dilatation of about 2 microstrain, were exceeded. In particular the two events that violate the approximate threshold (dashed line) in Figure 7 do not violate the thresholds shown here. From Figure 8, however, it is not possible to know whether effective strains or the dilatations are the cause of triggering. We note that effective strain level for the Valley of Mexico is similar to the strain associated with triggered activity in western Nevada after the Landers earthquake (Anderson *et al.*, 1994; Bodin and Gomberg, 1994). It is worth pointing out that although the threshold seems to work, the amplitude of the strain pulse is not well correlated with the intensity of the triggered activity in the valley (compare seismicity after 1932 and 1985 in Figures 5b and f).

Table 3

Probabilities of Possible Outcomes of 7 Randomly Selected Time Intervals

Fig. 7. Distance and magnitude of earthquakes analyzed. Symbol type indicates whether Valley of Mexico earthquakes were triggered by the coastal earthquake. The straight line divides events with or without triggered seismicity, with a few exceptions. In this figure the delayed seismicity following the September 19 and 21, 1985 earthquakes and the June 3 and 18, 1932 earthquakes is attributed to the mainshocks only.

Fig. 8. Synthetic strains from each of the large earthquakes analyzed. These were computed for the location of Tacubaya in the Valley of Mexico at a depth of 4 km. All synthetics use a point-source approximation. Top: Effective dynamic strain. Bottom: Dilatation. Events to the left of the vertical dashed line caused triggering while those to the right did not. Note that the triggered earthquakes are associated with effective strains and dilatations greater than about 3 and 2 microstrains, respectively

DISCUSSION AND CONCLUSIONS

Our observations suggest that some major earthquakes along the Mexican subduction zone are followed by a statistically significant increase in the seismicity in the Valley of Mexico. We further find that during the earthquakes which caused an increase in the seismicity, a threshold in the effective dynamic shear strain of about 3 microstrain, and in the dilatation of about 2 microstrain was exceeded. These conclusions lead us to believe that a causal, triggering mechanism is likely to be present. However, there are two issues which need to be elucidated. The first is the delay of about a month that occurs in about half of the cases of triggered seismicity. The second is the lack of correlation between the amplitude of the triggering strains and the intensity of the sequence of triggered events.

There were delays in the triggered events after the Landers earthquake, with some triggered events occurring up to 3 months after the main shock. However, the delays were, on average, greater in the Mexico City case. Anderson *et al.* (1994) speculated that the Landers earthquake triggered creep on faults that were near to failure, and that this creep accelerated in some cases to cause the observed events. The proximity of the fault to failure would determine the time until the triggered event. In the case of Mexico City, an alternative mechanism could involve fluid flow.

In a fluid flow model, we assume that the strains induce fluid movements, possibly caused by some compaction of the sediments and consequent increases of pore pressure. Considering that the basin has only been closed for ~105 years (Urrutia *et al.*, 1994), continuing consolidation is expected, and further considering that a clay layer caps the basin sediments, this could force downward migration of water. The result could be shallow (i.e. 2-4 km depth) triggered earthquakes, caused by a mechanism much like that associated with reservoir induced seismicity, with delays associated with the time constant of the diffusion process. Order of magnitude estimates suggest that the month-long delays are reasonable. Hill *et al.* (1993) also recognized the possibility that a fluid diffusion process could account for delayed triggering.

Hydrologic conditions have changed in the Valley of Mexico since the 1940's. Before the 1940's, there was little pumping of ground water, and artesian conditions prevailed in several parts of the valley. At present, the artesian conditions no longer exist. This decrease in level of ground water could result in less increase in fluid pressure at depth and the smaller energy release in triggered events in 1985. This may also explain why the triggered seismicity following the 1978 and 1979 events is ambiguous.

Finally, we remain intrigued by the earthquakes in Mexico City that preceded some of the large coastal earthquakes. Unfortunately, it is beyond the scope of this study to carry out sufficient observations and statistical interpretation to conclude if there is significance to this coincidence.

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S. K. Singh1, J. G. Anderson2 and Miguel Rodríguez3

1 Instituto de Geofísica, UNAM, Cd. Universitaria, 04510 México, D.F.

2 Seismological Laboratory, Mackay School of Mines, University of Nevada, Reno, Nevada 89557

3 Instituto de Ingeniería, UNAM, Cd. Universitaria, 04510 México, D.F.

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