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MAGNITUDE AND EPICENTER ESTIMATIONS OF MEXICAN EARTHQUAKES FROM ISOSEISMIC MAPS

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RESUMEN

Mediante el estudio de algunos terremotos ocurridos en México se han podido derivar relaciones entre la magnitud, M, y las áreas A_i, delimitadas por los contornos correspondientes a intensidades IV, V y VI de la escala modificada de Mercalli de la forma $M = \lambda_i \log A_i + \mu_i$. Debido a la escasez de datos se ha fijado λ_i igual a 1. Los eventos se clasifican como "interplacas" (los que ocurren en la frontera entre las placas) e "intraplacas" (los que ocurren dentro de las placas). Dichas relaciones permiten estimar M dentro de un margen de ± 0.3 a ± 0.4 de unidad de magnitud (una desviación estandar) dentro de sus rangos de aplicabilidad ($7.0 \lesssim M \lesssim 8.2$ para interplacas y $6.4 \lesssim M \lesssim 7.1$ para intraplacas). La atenuación de las intensidades para los eventos interplacas es mayor que para los eventos intraplacas y es comparativamente igual o mayor que la de los temblores del sur de California. Los epicentros estimados en el centro del contorno de máxima intensidad difieren de los epicentros instrumentales en 48 ± 22 km.

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ABSTRACT

Relationships between magnitude, M, and areas, A_i, of modified Mercalli intensity contours IV, V and VI of the form $M = \lambda_i \log A_i + \mu_i$ are derived from Mexican earthquakes. Due to insufficient data, λ_i has been fixed to 1. Events have been grouped broadly as interplate and intraplate events. Within the range of their validity ($7.0 \lesssim M \lesssim 8.2$ for interplate; $6.4 \lesssim M \lesssim 7.1$ for intraplate) the relations would give estimate of M to within ± 0.3 to ± 0.4 unit (one standard deviation) of magnitude. The attenuation of intensity for interplate earthquakes is higher than that for intraplate earthquakes. The attenuation for interplate earthquakes is comparable to or greater than for Southern California earthquakes. Epicenters estimated at the center of maximum intensity contours differ from instrumental epicenter by 48 ± 22 km.

INTRODUCTION

The purpose of this paper is two fold: (1) to establish relationships for large Mexican earthquakes between magnitude and areas of different isoseismic contours, and (2) to compare epicenters estimated from isoseismic maps with instrumentally determined epicenters. Several studies on magnitude and isoseismic areas are available for other regions, e.g., Toppozada (1975) for California and Western Nevada region. Toppozada (1975) also gives an extensive reference on the subject.

Our study will be useful in estimating magnitudes and epicenters of those earthquakes of Mexico for which the only information available is felt and damage reports. For example, it is possible to construct rough isoseismic maps for last century's large earthquakes of Mexico. It will be very useful to estimate magnitudes and epicenters of these events and to quantify the uncertainties in these estimates (Singh *et al.*, 1981 b). Relationships between magnitude and areas under different intensity contours will also be useful in estimating areas affected at various intensity levels for a given magnitude event. Our experience in reading damage and felt reports for the past as well as the present century's earthquakes in Mexico suggests that the areas of modified Mercalli (MM) intensity contours ≥ VII cannot be considered reliable due to sparse population density, especially along the Pacific coast of Mexico. Isoseismic maps of Mexican events generally show contours down to intensity III. At intensity III, the motion may not be recognized as an earthquake (Richter, 1958, p. 137) and it may not be reported. Thus, only the areas of intensities IV, V and VI are considered reliable by us. In view of this, we have restricted our analysis to the MM intensity contours IV, V and VI only.

Esteva (1968) obtained the following expression relating magnitude, M, hypocentral distance, R(km), and intensity, I, for earthquakes in Mexico: $I = 1.45\,M - 4.7 \log_{10} R + 7.9$. Our analysis differs from Esteva's in that (a) we consider only

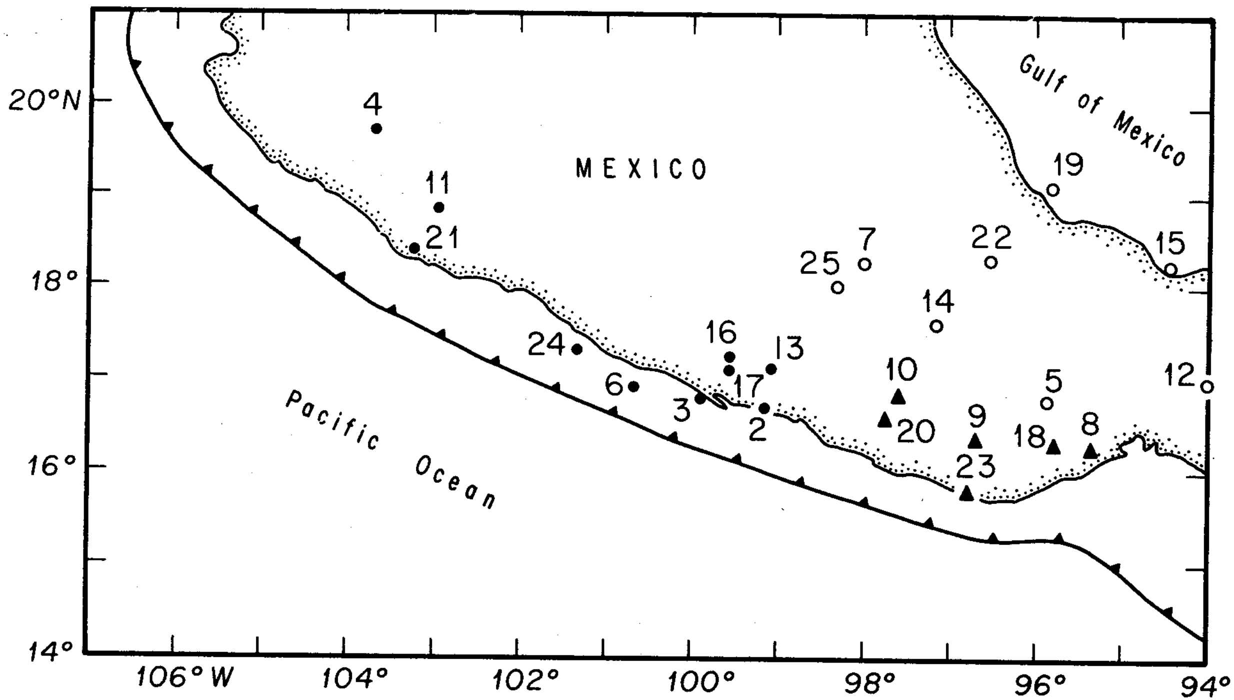

Fig. 1: Epicenters of the events from Table 1. Solid dots and triangles are interplate events and open circles are intraplate events. Solid dots are events in Guerrero and northwest of Guerrero and solid triangles are events in Oaxaca. Number in the figure refers to the event number in Table 1. Event 1 lies outside the map.

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the three MM intensity levels mentioned above, (b) while Esteva treated all events similarly, our data easily divide into interplate and intraplate events, and (c) the data set available now is somewhat larger and some of the magnitudes have been revised since the time of previous analysis.

DATA

The earthquakes for which isoseismic maps as well as instrumentally determined magnitudes and epicenters are available are listed in Table 1. Isoseismic maps of

Tabla 1

Data. Areas under MM intensity IV, V, and VI from isoseismic maps of Figueroa (1963, 1971, 1974a, 1974b, 1975, 1979) except events 16, 17. For other references on the data see Singh *et al.* (1981a).

Event No.	Date	Lat °N	Lon °W	Mag	Depth	Areas (km^2) I ≥IV	I ≥V	I ≥VI
1	Sept. 23, 1902	16.0	93.0[1]	8.2[1]	S[1]	486,000	270,000	162,000
2	Mar. 26, 1908	16.7	99.2	7.8[3]	80±	347,900	174,000	85,800
3	Jul. 30, 1909	16.8	99.9	7.4	S	230,300	112,700	60,800
4	Jun. 7, 1911	19.7	103.7	7.7	S	269,200	138,500	94,200
5	Aug. 27, 1911	16.77	95.90[2]	6.75[3]	100	206,500	118,500	58,600
6	Dec. 16, 1911	16.9	100.7	7.5	50	225,900	121,500	60,700
7	Feb. 10, 1928	18.26	97.99[4]	6.5[3]	84	67,100	42,100	19,700
8	Mar. 22, 1928	16.23	95.45	7.5	S	234,100	157,800	105,200
9	Jun. 17, 1928	16.33	96.70	7.8	S	263,000	131,500	39,400
10	Aug. 4, 1928	16.83	97.61	7.4	S	163,100	84,200	36,200
11	Apr. 15, 1941	18.85	102.94	7.7	S	365,100	293,800	218,500
12	Nov. 9, 1956	17.0	94.0[5]	6.4[5]	150[5]	270,900	134,100	67,100
13	Jul. 28, 1957	17.11	99.10	7.5	S	514,000	376,700	224,500
14	May 24, 1959	17.61	97.17[5]	6.9[5]	63	210,400	159,100	91,000
15	Aug. 26, 1959	18.26	94.43[5]	6.75[5]	S	220,600	68,900	23,000
16	May 11, 1962	17.25	99.58	7.0	40	330,000[8]	206,900	130,400
17	May 19, 1962	17.12	99.57	7.2	33	390,000[8]	251,900	164,900
18	Aug. 23, 1965	16.3	95.8	7.6	20	391,900	260,900	146,200
19	Mar. 11, 1967	19.12	95.82[5]	5.5[5](mb)	47[5]	28,900	19,400	7,700
20	Aug. 2,1968	16.6	97.7	7.4	40	291,930	181,200	69,200
21	Jan. 30, 1973	18.39	103.21	7.5	32	675,100	500,000	222,700
22	Aug. 28, 1973	18.30	96.54	7.1	82	406,200	245,000	114,000
23	Nov. 29, 1978	15.77	96.80	7.8	20	275,800	146,900	57,000
24	Mar. 14, 1979	17.31	101.35	7.6	30	653,800	450,700	225,400
25	Oct. 24, 1980	17.98	98.32[6]	7.0[7]	≤50[6]	348,000	222,000	82,300

[1]Kanamori and Abe (1979) [5]NOAA earthquake data file (World-wide Earthquake Catalogue)
[2]Figueroa (1970) [6]J. Havskov (personal communication)
[3]Gutenberg and Richter (1954) [7]P.D.E. (U.S. Geological Survey)
[4]Jiménez and Ponce (1977-1978) [8]Isoseismic map by Merinq y Coronado *et al.* (1962).

all but two events (events 16 and 17) have been prepared by Figueroa (1963, 1971, 1974a, 1974b, 1975, 1979, unpublished reports). For the majority of the events (magnitude $\geqslant$ 7.0), location, magnitude and depth are taken from Singh *et al.* (1981a) where appropriate references are given. For the remaining events, the references are given in Table 1. Table 1 also gives areas of MM intensity contours IV, V and VI. These areas were measured with a planimeter. Open contours, especially for coastal earthquakes, were approximately closed by inspection. The error thus introduced in area estimation probably does not exceed 25%.

The magnitudes listed in Table 1 are M_s or M (as given in Gutenberg and Richter, 1954) except for event 19, which is m_b. M appears to be close to M_s at least for great shallow earthquakes (Geller and Kanamori, 1977; Abe and Kanamori, 1980). Here we shall assume that all magnitudes are M_s and shall denote them as M. Nuttli *et al.* (1979) suggest that MM intensity values are related to 1 Hz, Lg-wave ground motion and, therefore, should correlate with m_b. Toppozada (1975), in his study on regressions of magnitude vs. $\log_{10} A_i$, has used local magnitude, M_L. Hanks *et al.* (1975) have reported a linear relation between seismic moment, M_o, and $\log_{10} A_{VI}$ for Southern California earthquakes. Our principal interest in this study is to establish relationships for events with M $\gtrsim$ 6.4. As is well known, m_b and M_L saturate above about 7.0 (Hanks and Kanamori, 1979). For larger earthquakes, areas of intensity contours IV, V and VI should then correlate with M_s or M_W. For Mexican earthquakes, the saturation problem of M_s does not arise because of small rupture lengths ($\lesssim$ 100 km, Singh *et al.*, 1981a) and therefore we feel justified in using M_s for all events $\gtrsim$ 6.4.

ANALYSIS

Area, A_i, of the MM intensity contour, i, will depend on many factors, e.g., source parameters (magnitude, depth, focal mechanism, rupture characteristics, rupture area, stress drop, etc.), propagation path, local geology of the site, population density, etc. Limited number of data available (25 events) allows us only a broad classification of these earthquakes. From the plots of M vs. $\log_{10} A_i$, i = IV, V, VI, shown in Figures 2, 3, and 4, it can be seen that the data points form two distinct groups: interplate and intraplate with few exceptions. Anomalous nature of events 16 and 17 is, most probably, due to the fact that the isoseismic maps of these two events were not prepared by Figueroa. Thus, the simplest, tectonically most meaningful and that into which the data seem to naturally fall is classification in terms of interplate and intraplate events. It is reasonable to assume that for each classification, A_i may be related to the rupture area, A_o, by

$$A_i = C_i A_o^{\gamma_i} \tag{1}$$

where i = MM intensity level and C_i and γ_i are constants. Kanamori and Anderson (1975), Wyss (1979), and Singh *et al.* (1980a), among others, have related magnitude, M, to rupture area by

$$M = \alpha \log A_o + \beta \quad (2)$$

with $\alpha \sim 1$, then

$$M = \lambda_i \log A_i + \mu_i \quad (3)$$

where $\lambda_i = \alpha/\gamma_i$, $\mu_i = \beta - \frac{\alpha \log C_i}{\gamma_i}$. Due to limited number of events, small range of magnitudes ($7.0 \lesssim M \lesssim 8.2$ for interplate, $6.4 \lesssim M \lesssim 7.1$ for intraplate except for event 19, for which $m_b = 5.5$) and large scatter in data (Figures 2, 3, and 4) it is not possible to determine the slope, λ_i, by the least-squares method. For this rea-

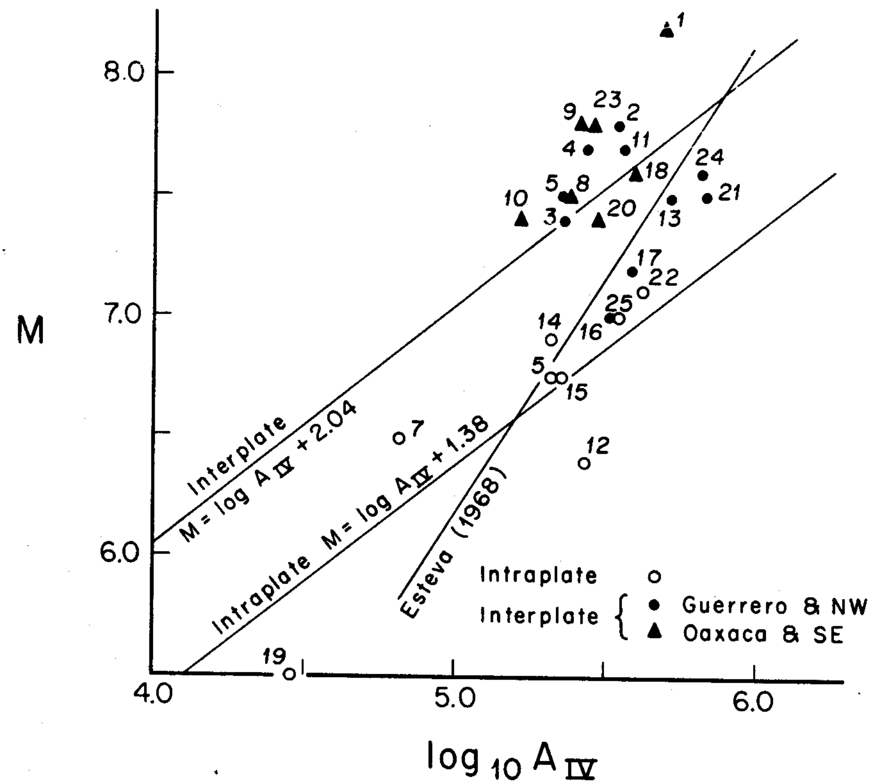

Fig. 2: M vs $\log_{10}A_{IV}$ where A_{IV} is the area (in km^2) of MM intensity contour IV. Symbols are the same as in Figure 1. Interplate: $M = \log_{10}A_{IV} + 2.04$; intraplate: $M = \log_{10}A_{IV} + 1.38$. Esteva's (1968) relation is shown for comparison.

son, we shall fix $\lambda_i = 1$. Since $\alpha \sim 1$, this implies that in equation (1) $\gamma_i \sim 1$. Toppozada (1975) for California and Western Nevada region has reported $\lambda_V = 1.09$ and $\lambda_{VI} = 0.85$. Wesnousky *et al.* (1981) have studied the relationship between seismic moment, M_o, and area of intensity IV on the Japanese Meteorological Agency (JMA) scale. JMA intensity IV roughly corresponds to MM intensity VI. The relationship given by Wesnousky *et al.* (1981) corresponds to $\lambda_{VI} = 0.88$. The values of Toppozada (1975) and Wesnousky *et al.* (1981) are close to $\lambda_i = 1$ chosen by us. With this fixed slope of $\lambda_i = 1$, the values of μ_i, i = IV, V and VI for inter- and intraplate events are given in Table 2. Note that at the same magnitude, the intraplate events given an area, A_i, about 4.7 (for intensity $\geqslant$ IV) to 8.5 (for intensity $\geqslant$ VI) times greater than the corresponding A_i for an interplate event. Intraplate events are generally deeper than interplate events (Table 1). Nevertheless, the geometrical spreading factor is unlikely to be the cause of the observed differences in areas at these intensity levels since depths are still, in general, much less than contour dimensions. Possible causes for larger attenuation rate for interplate events as compared to intraplate events may be (a) higher viscous losses close to the subduction zone, (b) greater scattering losses near the fractured interface, and (c) channeling of energy in the shallower (more absorbing) crust for interplate events. In the latter case, for the deeper intraplate events, the seismic energy may be spread out through less absorbing deeper layers. Howell and Schultz (1975) suggest similar mechanisms to explain the differences in isoseismal areas of eastern and western U. S. earthquakes.

For Southern California earthquakes, Hanks *et al.* (1975) found that

$$\log M_o = 1.97 \log A_{VI} - 2.55 \qquad A_{VI} \text{ in cm}^2 \tag{4}$$

where M_o = seismic moment. Since M_o for interplate events is related to M_s by (Hanks and Kanamori, 1979)

$$\log M_o = 1.5 M_s + 16.1 \tag{5}$$

it follows that

$$M_s = 1.31 \log A_{VI} + 0.70 \qquad A_{VI} \text{ in km}^2 \tag{6}$$

Figure 4 also shows relation (6). For the same magnitude event, Southern California earthquakes give a larger area under MM intensity VI contour than the interplate events in Mexico. This suggests a higher attenuation for deeper Mexican subduction zone earthquakes (depth $\gtrsim$ 30 km) than the shallower Southern California earthquakes (depth $\sim$ 10 km). A systematic underestimation of A_{VI} areas in Mexico could also explain this observation.

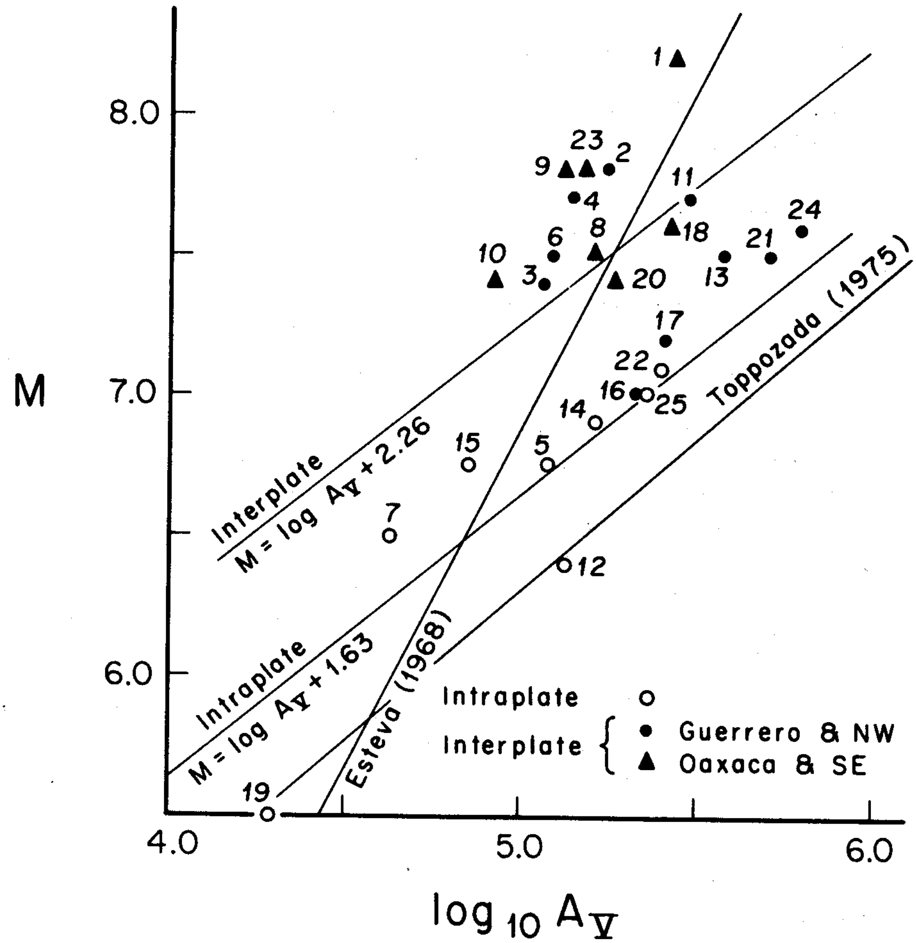

Fig. 3: M vs $\log_{10}A_V$. Symbols are the same as in Figure 1. Interplate: $M = \log_{10}A_V + 2.26$; intraplate: $M = \log_{10}A_V + 1.63$. Esteva (1968) and Toppozada's (1975) relations are shown for comparison.

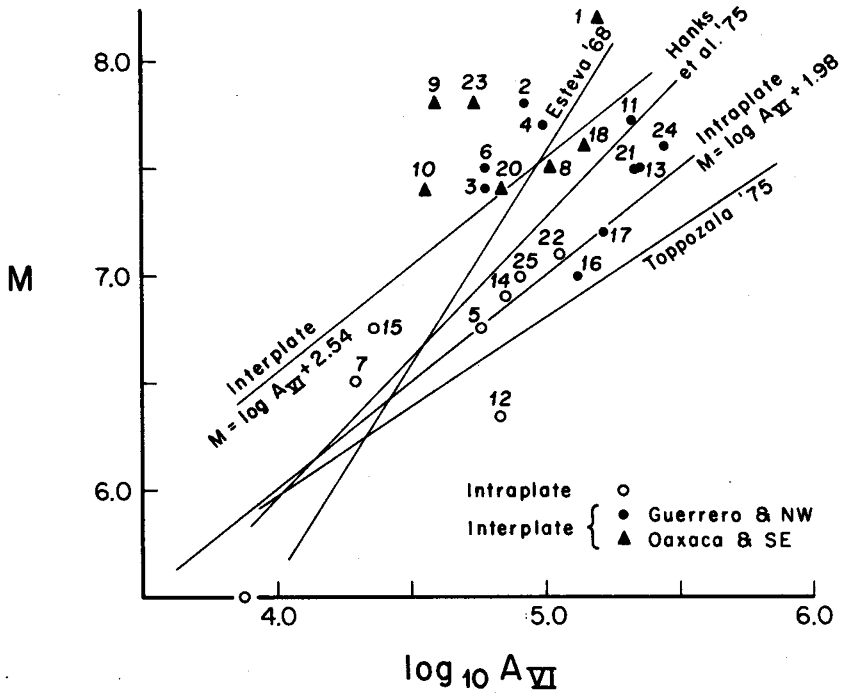

Fig. 4: M vs $\log_{10}A_{VI}$. Symbols are the same as in Figure 1. Interplate: $M = \log_{10}A_{VI} + 2.54$; intraplate: $M = \log_{10}A_{VI} + 1.98$. Relation $M = 1.313 \log_{10}A_{VI} + 0.70$ derived from Hanks *et al.* (1975) for Southern California is shown for comparison along with Esteva (1968) and Toppozada's (1975) relations.

EPICENTER FROM ISOSEISMIC MAPS

In the absence of an instrumentally determined epicenter, the center of maximum MM intensity contour could be used to estimate it. While the directivity of the source, the local geology, and the population density will, to an extent, affect the region of maximum damage, one would intuitively expect the location of maximum damage to be not too far from the epicenter (some care is needed in treating the intensities in Mexico City, where damages may be extensive even for coastal earthquakes). In order to quantify the difference, Δ, between instrumentally and isoseismically determined epicenters, in Figure 5 we have plotted Δ in km vs. year of the event. The data is from Table 1 and from isoseismic maps of Figueroa. Except for events 1, 2, 8, 21, 22 and 24, the difference, Δ, is less than 55 km. For the whole data set Δ is 48 ± 22 km and appears independent of year. [Note that the epicenters

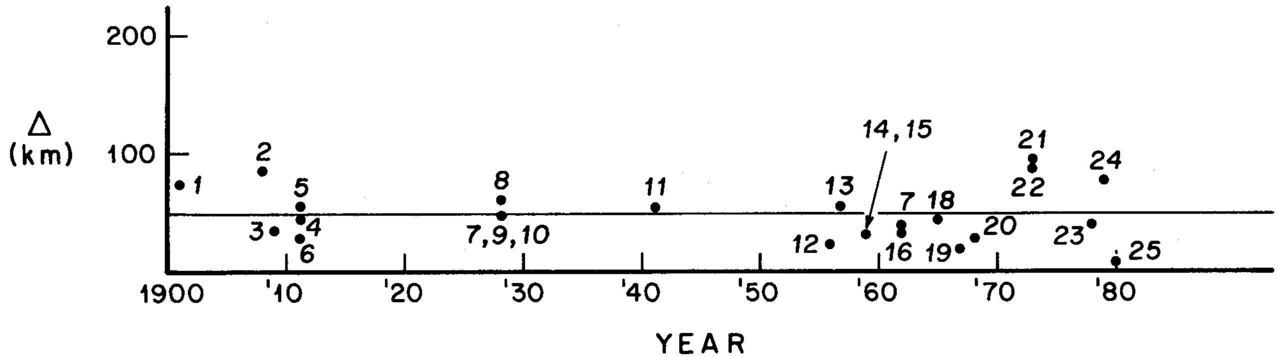

Fig. 5: Difference, Δ (km), in instrumental and isoseismal epicenter vs year of the event. Number refers to the event number in Table 1.

reported by P. D. E. (USGS) for some of the recent earthquakes in Mexico differ up to about 50 km from those determined from field seismographs (Singh *et al.*, 1980b; Meyer *et al.*, 1980).] It seems reasonable to conclude that epicenters can be estimated from maximum isoseismic contours within about 50 km for this century's earthquakes if adequate intensity data are available. For earthquakes of the last century, the error may be somewhat greater (probably $\lesssim 1^{o}$ for most large events) due to sparser population density and worse communication problems.

For large earthquakes, focusing of energy by the rupture process could lead to identification of the region of maximum intensity different than the epicenter. Both locations have significance in terms of the faulting process. The region of highest intensity is not in this case a mislocation of the event, but a redefinition of location in terms of maximum energy rather than rupture initiation. Local geology can, of course, modify the intensity pattern significantly.

EXAMPLES

(1) Let us consider the great earthquake of January 24, 1899. This is the only earthquake of last century in Mexico for which instrumental magnitude and epicenter are available. Gutenberg (1956) reported an epicenter of 17°N, 98°W with a quality factor D (= ± 5°). Kanamori and Abe (1979) have assigned it a magnitude $M_s = 7.9$. Our compilation of the intensity data from newspaper reports (Singh *et al.*, 1981b) is shown in Figure 6. Reports from many localities only say that the earthquake was felt or was strongly felt. We believe that a report stating that an earthquake was felt corresponds to MM intensity of IV (for strongly felt, intensity $\geqslant$ IV) for Mexico. Area under extrapolated intensity contour IV, A_{IV}, is about 550,000 km² which, according to the relation $M = \log A_{IV} + 2.04$ (Table 2), gives

Table 2

$$M = \log A_i + \mu_i$$

Intensity level. i	Interplate		Intraplate	
	μ_i	Standard error of M	μ_i	Standard error of M
IV	2.04	±0.30	1.38	±0.28
V	2.26	±0.35	1.63	±0.29
VI	2.54	±0.40	1.98	±0.30

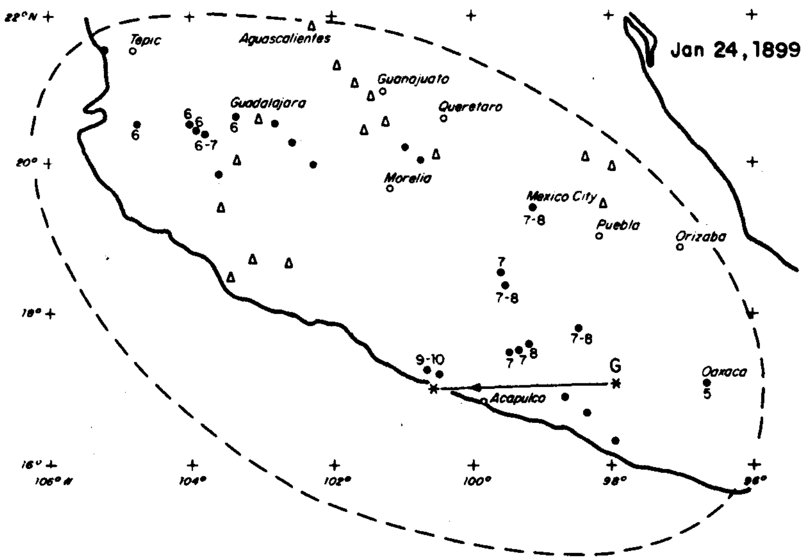

Fig. 6: Intensities for January 24, 1899 earthquake. Arabic numbers refer to MM intensities. Open triangle: earthquake felt (intensity = IV), solid circle: strongly felt (intensity ≥ IV). Dashed line encloses area of intensity ≥ IV (estimated as 550,000 km^2) which gives M = 7.8 as compared to M_S = 7.9 reported by Kanamori and Abe (1979). Star with G shows Gutenberg's (1956) epicenter. The star connected by an arrow with G shows epicenter determined from damage reports.

M = 7.8. This value is close to the value of M_S = 7.9 assigned by Kanamori and Abe (1979). Extensive damage and many aftershocks were reported near the town of Tecpan, northwest of Guerrero, where intensities were IX - X. Our estimation of epicenter (close to Tecpan) is 17.0°N, 100.6°W, which is more than 2°W of Gutenberg's (1956) epicenter. In this case, we believe that the isoseismically estimated epicenter is more accurate (probably within 1°) than the instrumentally determined epicenter.

(2) Table 3 gives six earthquakes for which Figueroa (1963, 1971) has published isoseismic maps. These events are not listed in world-wide catalogs. Since such catalogs are supposed to be complete for all events with $M_S \geq 7.0$ since 1904 (Duda, 1965), presumably the events listed in Table 3 were smaller than M_S = 7.0. Magnitudes assigned by Figueroa (1970) as well as those estimated from areas of intensity IV, V and VI contours, using relations given in Table 2, are shown in Table 3. M for a given event estimated from areas of different contours are reasonably consistent with one another. Magnitudes assigned by Figueroa (1970) for events 3, 5, and 6 differ from those estimated from isoseismal areas by 0.5 to 1.0 unit. It is unlikely that event 6 had a magnitude of 7.7 as reported by Figueroa (1970) since it is not listed in world-wide catalogs. Based on isoseismal areas, all events except 6, in Table 3, have M ≃ 7.0. It would be interesting to determine magnitudes of these events from seismograms.

Table 3

Estimated magnitudes of some Mexican earthquakes from isoseismal areas. Data on location, origin time and magnitudes from Figueroa (1970). Isoseismic maps from Figueroa (1963, 1971). Except for Event 6, all earthquakes are taken as interplate events.

Event No.	Date	H	M	S	Lat°N	Lon °W	Depth (km)	M (Figueroa, 1970)	A_{IV} (km^2)	$M(A_{IV})$	A_V (km^2)	$M(A_V)$	A_{VI} (km^2)	$M(A_{VI})$
1	Jan. 16, 1902	23	19	00	17.6	99.7	—	7.0	121,000	7.1	57,000	7.0	13,500	6.7
2	Jul. 31, 1909	18	43	10	16.6	99.4	—	7.0	156,000	7.2	84,000	7.2	33,600	7.1
3	Sep. 5, 1909	11	17	20	16.5	99.7	—	6.6	156,000	7.2	60,500	7.0	30,200	7.0
4	Oct. 31, 1909	-------			17.0	101.2	—	7.0	82,000	7.0	50,500	7.0	28,500	7.0
5	May 31, 1910	04	19	19	16.7	99.2	—	6.5	185,000	7.4	100,700	7.3	50,300	7.2
6	Apr. 17, 1928	03	26	15	17.8	97.2	100	7.7	153,000	6.6	90,000	6.6	59,400	6.8

CONCLUSIONS

Under two broad classifications of interplate and intraplate earthquakes, we have determined relationships between magnitude, M, and areas, A_i, of MM intensity contours IV, V and VI of the type: $M = \lambda_i \log A_i + \mu_i$ for Mexican earthquakes. Due to insufficient data, we chose $\lambda_i = 1$. Although there is no theoretical basis for fixing the slope λ_i to 1, the analysis for California and Western Nevada data, with local magnitude, M_L, gives $\lambda \sim 1$ for A_V and A_{VI} (Toppozada, 1975). For intraplate events in Japan, Wesnousky *et al.* (1981) find $\lambda_{VI} = 0.88$. While more accurate estimation of λ_i is needed and must await further data, the relations given in this paper can be used in estimating M from A_i (i = IV, V and VI) in the range $7.0 \lesssim M \lesssim 8.2$ for interplate, and $6.4 \lesssim M \lesssim 7.1$ for intraplate earthquakes. The standard errors in using these relations, given in Table 2, are between ± 0.3 to ± 0.4 unit of magnitude. The results suggest a higher attenuation for the Mexican subduction zone than for Southern California. Interplate events show larger attenuation than intraplate events in Mexico. Although intraplate events, on the average, are deeper than interplate events, geometric spreading is not likely to be the cause for this difference. Possible explanations may be higher viscous and scattering losses near the subduction zone and/or channeling of energy in the more highly attenuating surface layers for seismic waves from interplate events as compared to intraplate events.

The difference between instrumental and isoseismal epicenters is found to be 48 ± 22 km. Thus, for well reported earthquakes of this century and the last century, the center of the maximum MM intensity contour can be used to estimate epicenter to within $1/2^o$ and 1^o, respectively.

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