PRELIMINARY EVALUATION OF THE VOLCANIC HAZARD IN THE SOUTHERN VALLEY OF MEXICO

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RESUMEN

La ciudad de México está ubicada en el centro de un campo volcánico activo en la cuenca del Valle de México. Dejando de lado la actividad histórica del gran estratovolcán Popocatépetl, la última actividad de este campo volcánico fue la del volcán monogénico Xitle. Esta erupción ocurrió el año 2500 A.C. En este trabajo se calculó la tasa de erupción para el campo volcánico del sur del Valle de México por varios métodos diferentes. La tasa de erupción media se comprobó que es de 10^{-3} erupciones/año. La máxima probabilidad de erupción en el sur del Valle de México está situada en una banda E-O que pasa a través de la Sierra de Chichinautzin. Por razones de seguridad, la expansión del área metropolitana de la ciudad de México deberá alejarse de la Sierra de Chichinautzin.

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ABSTRACT

Mexico City is located in the middle of an active volcanic field in the graben of the Valley of Mexico. Apart from the historical activity of the large stratovolcano Popocatepetl, the last activity of this volcanic field was from the monogenic volcano Xitle. This eruption occurred in the year 2500 B.C. In this article, the eruption rate for the volcanic field of the southern Valley of Mexico was calculated by several different methods. The mean eruption rate was found to be 10^{-3} eruption/year. The highest probability of volcanic eruption in the southern Valley of Mexico lies in an E-W band through the Sierra de Chichinautzin. For safety, the growth of the metropolitan area of Mexico City should be away from the Sierra de Chichinautzin.

INTRODUCTION

Volcanic phenomena, volcanic hazards, and volcanic activity forecasting have been extensively discussed in the literature (Decker 1973; Barberi and Gasparini 1976). A statistical approach has been used in volcanic activity forecasting (Wickmann 1966 and 1976; Rose and Stoiber 1969; Carta *et al.*, 1977). This method is based upon the historical activity record of a number of central volcanoes in an area. Evaluation of a stochastic model of a volcano give the probability of its eruption during a given interval of time.

Problems arise in the study of volcanic fields that extend over thousands of square kilometers. The monogenetic centers of volcanic activity can spread widely with no central focal point, according to the tectonic control of the volcanic field.

The aim of this paper is to evaluate the volcanic hazard of the volcanic field of the southern Valley of Mexico (S.V.M.) in the proximity of Mexico City.

Geology

Plio-quaternary volcanism in Mexico (Fig. 1) is mainly distributed in the Mexican Volcanic Belt (M.V.B.). This belt is an elongated structure of E-W direction with a calc-alkaline composition (Negendak 1972; Demant and Robin 1975). It is related to the subduction of the Cocos plate under the Central American continent (Hanuš and Vaněk 1978). Plio-quaternary volcanism of an alkali-basaltic composition is present along the eastern coast of Mexico, as well as in the peninsula of Baja California. The latter is related to the active spreading area of the Gulf of California (Demant and Robin 1975).

The largest volcanic fields are in the State of Michoacan and in the Valley of Mexico. The last volcanic activity in the State of Michoacan was that of Paricutin, from 1943 to 1952. The last volcanic activities in the Valley of Mexico were those of Xitle, in 2500 B.C. (Libby 1952),

and Popocatepetl, in 1920. Volcanic activity has occurred in the Valley of Mexico since the Pliocene epoch.

The Valley of Mexico is a graben structure on the crossing of two systems of faults of NW-SE and NE-SW direction. The more recent activity is emplaced on a fracture system of approximately E-W direction (Mooser 1974). The Sierra de Chichinautzin is part of this fracture system. Monocentric cones with large lava flows are the main type of activity.

METHODS

Eruption Probability

A stochastic approach to the evaluation of eruption probability during a given interval of time was first developed by Wickmann (1966). It is based on the historical record of eruption and the repose times for a given volcano. The eruption rate

$$\Phi(x) = \lim_{\Delta x \to 0^+} \frac{\text{prob } x < X < x + \Delta x / x < \Delta x}{\Delta x}$$

gives the probability that a volcanic event X will occur between time x and $x + \Delta x$, when Δx tends to 0^+. The eruption rate is the graphical derivative with respect to time, evaluated on a semilog plot, of the number of known repose periods of the volcano as a function of the length of each period.

The assumptions are:

a) one must know the precise time of eruption and repose;

b) the eruption time must be a non-negative random variable;

c) the activity of the volcano during a repose period must be describable by n states, each with a relative probability (P_i) where the $\Sigma P_i = 1$; and

d) only a limited number of kinds of eruption are allowed for each state.

As far as we know, the stochastic method of calculating the eruption rate has been applied only to central volcanoes (Wickmann 1966 and

1976; Rose and Stoiber 1969; Carta *et al.*, 1977). The lack of historical data from volcanic fields has, until now, prevented the application of the method to more extended areas. Figures 2a and 2b give examples of this method used with data from two Mexican volcanoes.

The volcano Popocatepetl has an eruption rate of 2.4×10^{-2} years^{-1}. The volcano Colima's eruption rate is 5×10^{-2} years^{-1}.

The volcanic activity in the M.V.B. is related to the subduction of the Cocos plate under the Central American continent (Hanuš and Vaněk 1978). It is reasonable to assume that, at least in historical times, (1) the volcanic activity in the M.V.B. is a stochastic process independent of time, and (2) the eruption time is an aleatory variable. The eruption rate concept was applied to all of the M.V.B. in order to obtain the probability of eruption over the entire area. The eruption rate obtained 7×10^{-2} years^{-1} is shown in Figure 3. The largest contribution to the eruption rate is from the two active volcanoes Colima and Popocatepetl.

A second method must be used when no historical record is available. If the geology of an area is known with sufficient accuracy and the geo-chronological data are available, a good approximation of the eruption rate is given by the ratio between the number of volcanic events in the area and the interval of time in which they occurred.

The Sierra de Chichinautzin is the most relevant part of the volcanic outcrop of the S.V.M. A paleomagnetic study of this area found no presence of sites with reversed magnetism (Mooser *et al.*, 1974). This indicated an age younger than 0.7 Myr. Two hundred thirty-six volcanic events were counted in the area (Fig. 4). Included in this number were the two stratovolcanoes Popocatepetl and Ixtlaccihuatl. Each one was counted as a single event in order not to obscure the general trend of the volcanic field. The number of events included cones and domes indicated in the geological plane (Mooser 1974) as Qcbc and Qad of quaternary age. With these data we obtained an eruption rate of 0.31×10^{-3} er/yr. This value is probably a lower limit because it does not take into account the volcanic centers which were covered by subsequent activity during the last 0.7 Myr.

The eruption rates for two other volcanic fields were calculated by

this metod. In the archeological zone of Tlapacoya (Mooser 1969), twelve volcanic events were counted during the last 23,000 years. This gave an eruption rate of 0.53×10^{-3} er/yr. In the SW part of the Sierra de Chichinautzin, a morphological study and C^{14} datings (Bloomfield, 1975) were made of 41 volcanic cones formed within the last 40,000 years. The resulting eruption rate was 1.03×10^{-3} er/yr.

A third method of calculating the eruption rate is to divide the total volume of volcanic products of an area by the mean volume of products erupted by a single volcanic center. A rough evaluation of the total volume of lava in the S.V.M. is 1500 km^3. A cones has a mean volume of 0.5 km^3 of lava, as inferred from the mean volume of lava of 41 recent cones in the SW part of the Sierra de Chichinautzin (Bloomfield, 1975). A cone probably has 1 km^3 of pyroclastics, as inferred from the eruption of Paricutin (Fries, 1953). These data gave a result of 1000 events during the last 0.7 Myr in the S.V.M. The eruption rate was 1.43 $\times 10^{-3}$ er/yr.

A summary of the eruption rates calculated for the S.V.M. is given in Table 1. There is close agreement between the results obtained from the methods used. With these results it is reasonable to assume that the eruption rate of the S.V.M. is 10^{-3} er/yr (mean of the results: 0.83×10^{-3} er/yr). The results obtained with the geochronological method seem to be the most accurate. These calculations of the eruption rate of the S.V.M. do not take into account the activity of Popocatepetl. The activity of Popocatepetl is probably not related to the activity of the rest of the volcanic field in the S.V.M. The danger to because of its distance from inhabited centers.

Volcanic Zoning

The distribution of volcanic events in the S.V.M. is not a spatial aleatory variable, because the distribution depends upon the tectonic control of the volcanic field. In order to evaluate the distribution of events, the area was subdivided by means of a grid (Fig. 4) with squares of 7.5 km^2.

These squares cover a homogeneous geological area. In Figure 5, eleven N-S profiles and eight E-W profiles describe the distribution of the number of volcanic events in the area. The large number of events gives a sufficient statistical accuracy. The main feature shown in Figure 5 is the pronounced peak of the central N-S profiles. This peak indicates a preferential alignment of volcanic activity along the E-W direction in the central part of the Sierra de Chichinautzin. This agrees with the relationship of the younger volcanic fields with the active system of fractures of E-W direction in this area. The three E-W central profiles (3, 4, 5) contain about 75% of the observed number of volcanic events. The two northernmost profiles (1, 2) include 10% of the events, and the three southernmost profiles (6, 7, 8) contain 15%.

Considering the absolute eruption rate in each profile to be the product of the mean eruption rate of the total area (Φ_m) times the frequency of events (n) in each profile:

$$\Phi = n \Phi_m$$

we obtain:

profiles $1 + 2$: 0.10×10^{-3} er/yr

profiles $3 + 4 + 5$: 0.75×10^{-3} er/yr

profiles $6 + 7 + 8$: 0.15×10^{-3} er/yr.

CONCLUSIONS

The eruption rate of the southern Valley of Mexico was calculated by several different methods. The mean eruption rate calculated by these methods was 10^{-3} er/yr. This value is two orders of magnitude less than the eruption rate calculated for the entire Mexican Volcanic Belt. It is also one order of magnitude less than the eruption rate calculated for the two active volcanoes Popocatepetl and Colima.

The probability of eruption is distributed over a large area of $1900\,km^2$. The central E-W band of the S.V.M. has the highest probability of eruption.

The risk from an eruption is proportional to the absolute probability of eruption and to the amount of possible damage that it can cause. The metropolitan area of Mexico City is in rapid expansion (twelve million inhabitants in 1978) and is now approaching areas with a relatively high probability of eruption. The volcanic risk is increasing to values comparable with that of other areas which have a higher absolute probability of eruption, but have a lower risk to human life. In this respect it would be safe to plan the growth of Mexico City away from the E-W zone of the Sierra de Chichinautzin which has the highest probability of volcanic eruptions that can cause large economic and human loses.

ACKNOWLEDGEMENTS

TABLE 1

Eruption rates calculated for the southern Valley of Mexico

| Location	Method	Time (years)	Number of events	Eruption rate ($\Phi \times 10^{-3}$ er/yr)
Entire southern Valley of Mexico	Volume of Volcanic Products	700,000	1000	1.43
Sierra de Chichinautzin	Geological Method	700,000	236	0.31
Archeological Zone, Tlapacoya	Geoarcheological Method	23,000	13	0.53
SW part of the Siera de Chichinautzin	Geochronological Method	40,000	41	1.03
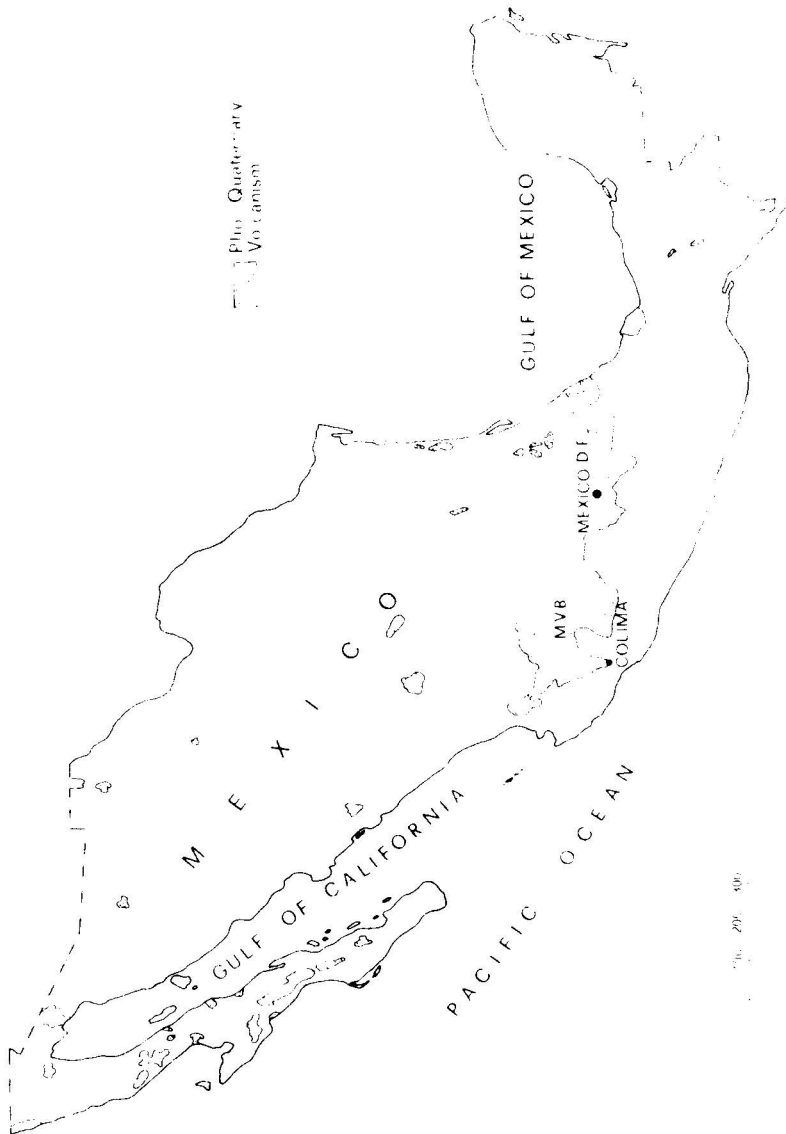
Figure 1. The Plio-quaternary volcanic fields in Mexico.
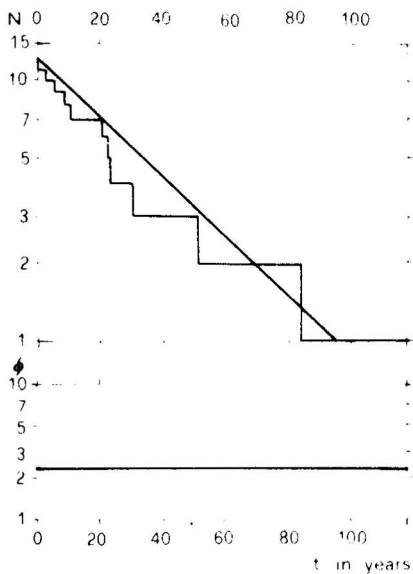
a)
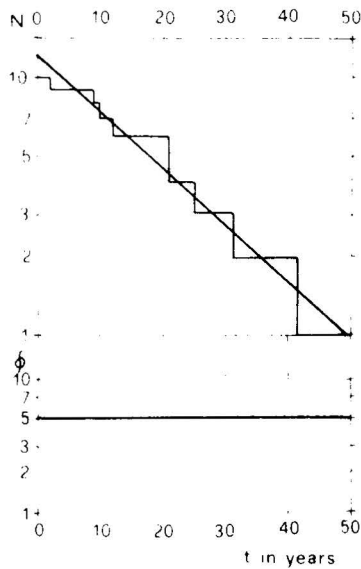
b)

Figure 2 a: Volcano Popocatepetl. The step function of the upper graph is the number, N, of reposes with durations longer than t years. The lower graph gives the eruption rate measured in 10^{-2} years^{-1}.

    This example is from Wickmann (1966).

Figure 2 b: Volcano Colima. The step function of the upper graph is the number, N, of repose periods with durations longer than t years. The lower graph gives the eruption rate measured in 10^{-2} years^{-1}. The data used to calculate the eruption rate are from Mooser (1958).
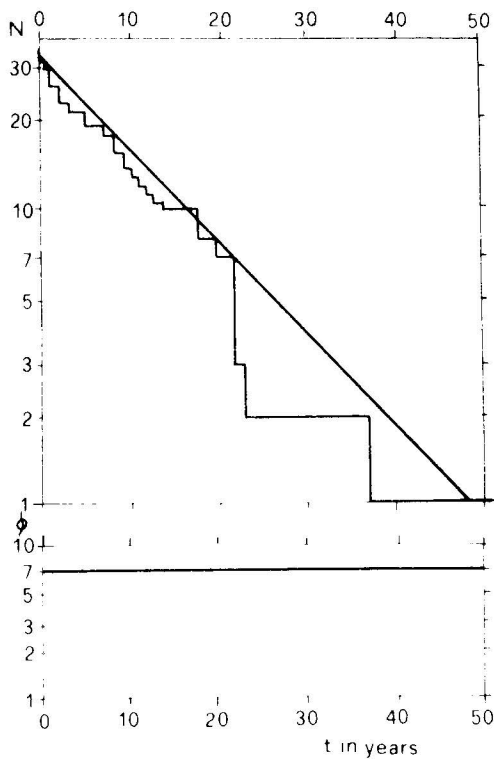
fig. 3

Figure 3. Entire Mexican Volcanic belt. The step function of the upper graph is the number, N, of repose periods with durations longer than t years. The lower graph gives the eruption rate measured in 10^{-2} year^{-1}. The data used are from Mooser (1958).
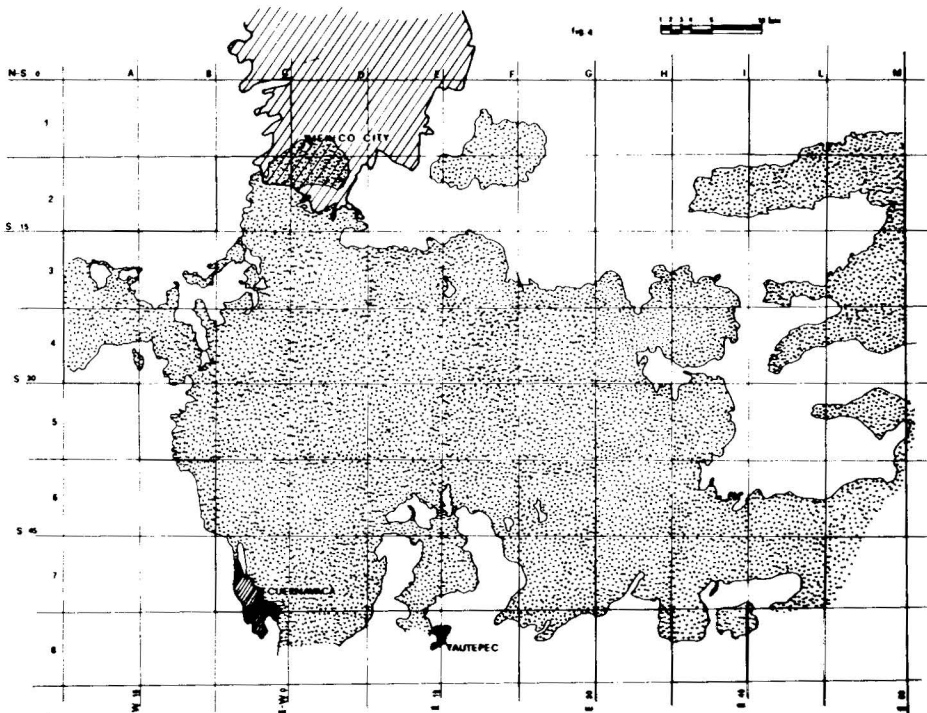
Figure 4. The Quaternary volcanic outcrop in the southern Valley of Mexico with the grid of reference for counting the number of volcanic events shown in the profile of Figure 6.
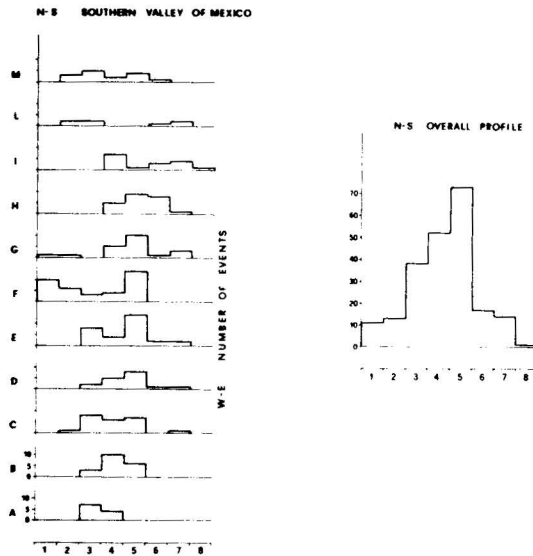
Figure 5. N-S profiles (letters) of the number of volcanic events counted in each square of 7.5 km^2 in the southern Valley of Mexico. The number on the ordinate give the number of events. The numbers on the abscissa are the references to the W-E profiles.

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