

A statistical study of the microseismicity near Messina *

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ABSTRACT

The application of the statistical analysis to a series of microshocks originating in the Messina area allows to determine the level and the type of interdependence between those events.

The investigation aims to identify an "occurrence model" compatible with the series in question, and shows the inadequacy of the simple Poisson process to describe the phenomenon observed; the series of events in question can, instead, be represented as a succession of periods of activity — conforming to a compound Poisson distribution — separated by intervals of seismic inactivity of varying duration.

The results reported here seem very correlated with those from an analysis of the spatial distribution of the activity; moreover, they are of interest for comparison with the characteristics of other regions, and constitute data that can be used for a more complete characterization of the structures which originate the activity itself.

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RIASSUNTO

L'analisi statistica di una sequenza di micrososse originanti in prossimità di Messina consente la determinazione del livello e del tipo di interdipendenza esistente fra gli stessi eventi.

L'indagine, diretta ad individuare un "occurrence model" compatibile con le caratteristiche della sequenza in esame, evidenzia l'inadeguatezza del processo di Poisson semplice a descrivere il fenomeno osservato e rivela che la sequenza degli eventi considerati può essere rappresentata come una successione di periodi di attività — conformi ad una distribuzione di Poisson composta — separati da intervalli di quiete sismica di durata variabile.

I risultati qui esposti appaiono ben correlabili con quelli provenienti da un'analisi della distribuzione spaziale dell'attività e, oltre a rappresentare un interessante elemento per il confronto con le caratteristiche di altre regioni, costituiscono un dato utilizzabile per una più completa caratterizzazione delle strutture "origine" dell'attività stessa.

INTRODUCTION

By applying the statistical analysis to a temporal sequence of seismic events, one can obtain — and the literature of the last twenty years offers numerous examples of this — useful information about the interrelations between the events themselves; consequently it is possible to determine the characteristics of the structures that have given origin to them.

The statistical method often employed for studying the high-intensity earthquakes is also widely applied in research on medium- and low-energy earthquakes. That is easily understandable if one considers the large number of medium and small shocks originating in a few years in the seismic areas.

The preliminary approach generally aims to establish the interdependence level of the events originating during a given period of time in the region under investigation; this is done by comparing the origin time series of the shocks with the Poisson statistical model which, as is well known, is valid for independent events. The low level of adaptability of this model with seismic phenomena has been widely discussed and interpreted by numerous authors (Knopoff, 1964; Vere-Jones et al., 1964;

Oliver et al., 1966; Ferraes, 1967; Shlien and Toksöz, 1970; Knopoff et al., 1972; Savage, 1972; Gardner and Knopoff, 1974; Rice, 1975; Udias and Rice, 1975); some of them (Shlien and Toksöz, 1970), however, observe a gradual tendency towards independence of the events when their focal depth increases. The disagreement between the theoretical Poisson model and the observational data is due to the presence, in the samples considered, of periods of inactivity too high compared with those estimated by the theoretical calculation. That is related (Knopoff, 1964) to the after-shock phenomenon and more generally to the tendency of the events to occur in temporal clusters, giving rise to the so-called bursts of activity.

These phenomena are well explained by more or less recent seismological theories and imply an interdependence of the events that various authors have attempted to describe by introducing new statistical models.

A trigger model has been proposed by Vere-Jones and Davies (1966) to describe some characteristics of the temporal distribution of the seismic events; most recently Knopoff (1971) faced the statistical problem introducing the variable "potential energy of deformation of the active structure". This model has been even applied with satisfactory results in the case of volcanic swarms (Filson and Simkin, 1975).

We consider it safe to say that when statistical investigation is applied to the seismological data it is generally able to provide usefully information for understanding the phenomena and for characterizing the active structures, above all when the information collected can be correlated to that coming from complementary methodologies.

In this paper the statistical investigation is applied to the sequence of microseisms observed at the seismic station of the University of Messina (MES) in the five-year period 1976-1980. The area is among those with the highest seismic risk in Italy; it is subject to tectonic mechanism of distensive type that can be inserted into the more complex geological picture (Fig. 1) of the Calabro-Peloritan Arc (Ortolani, 1975; Ghisetti and Vezzani, 1978; Selli, 1978).

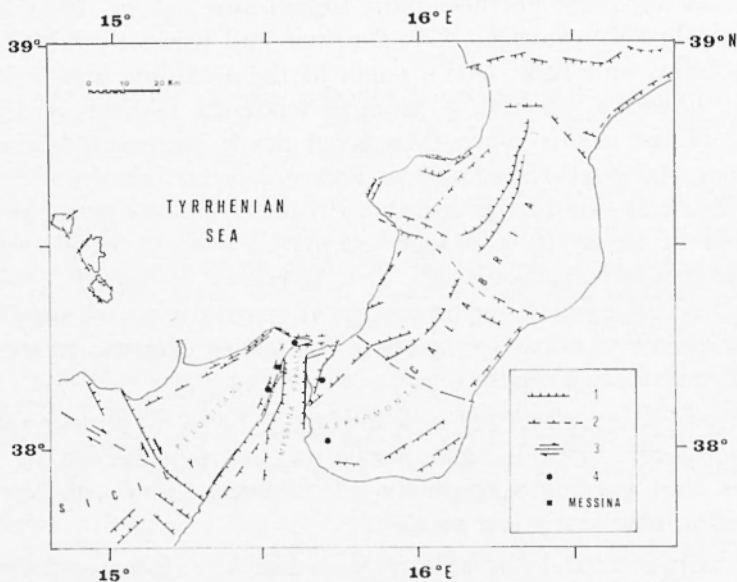


Fig. 1 - Main structures of the Southern zone of the Calabro-Peloritan Arc. The Messina Strait Graben is sited between two ranges (up-lifted): the Peloritani Mountains and the Aspromonte Massif. Symbols legend: 1 = fault (barbs on downthrown side); 2 = inferred fault; 3 = strike-slip fault; 4 = seismic stations.

Until a few years ago the seismic activity of this area was monitored only by the stations of Messina University, Reggio Calabria (RCI) and Messina I.N.G. (MSI). Since 1978 this work has also been done by the short-period seismic network of the Strait of Messina (Bottari et al., 1979; Bottari et al., 1981) which is at the present formed by four peripheral stations connected telemetrically to the central one (MES; Fig. 1 and 6).

DATA

The temporal distribution of the local seismic activity observed at the station of Messina University in the period January 1976 - October 1980 is here analysed.

The object of our statistical study, the series $\{t_i\}$ of the shock times, has been prepared taking those events — recorded at Messina on short-period Girlanda seismometers (Girlanda, 1963) — for which the $S-P$ difference is less than 3 sec and the magnitude M is not less than 1.3. The values of M were calculated taking the maximum amplitudes A_m observed on the Girlanda horizontal components and the epicentral distances D from Messina obtained from the $S-P$ values on the basis of a local crustal model, and then by extrapolating a relation $M = f(A_m, D)$ that is valid for earthquakes of intermediate energy.

The value of 3 sec, assumed for the upper limit of the $S-P$ difference, defines, according to the MSM model (Bottari et al., 1979) an approximately semispherical region having a radius of about 20 km and its center in Messina.

We consider that this choice of limits for the variables $S-P$ and M (3 sec and 1.3 respectively) takes account of the noise level observed at MES especially in the winter months and allows the condition of completeness of the $\{t_i\}$ (Udias and Rice, 1975) set to be satisfied.

The upper limit imposed on the $S-P$ difference excludes from the set the more energetic shocks ($M > 3.0$) occurring in the Strait of Messina and in the surrounding areas in the period in question. Thus, the object of our study is really the microseismicity near Messina.

The events selected show generally (in ab. 90% of the cases) an $S-P$ difference of between 1.5 and 2.5 sec, and present — on the MES seismograms — extremely similar seismographic characteristics. Two of these recordings are reported in Fig. 2a.

At Ganzirri, too, the recordings appear fairly similar one to another (Fig. 2b) although being less clear and detailed than those at Messina; at Ortì (Fig. 2c), where the instrument amplification is about fourfold compared with that chosen for the Messina instruments, the recordings are rarely readable and only in a few cases allow the P and S phases to be identified.

In a previous work (Bottari et al., 1981) reference was made to the results obtained in the ten or so cases in which it was possible to determine the focal coordinates of these events by

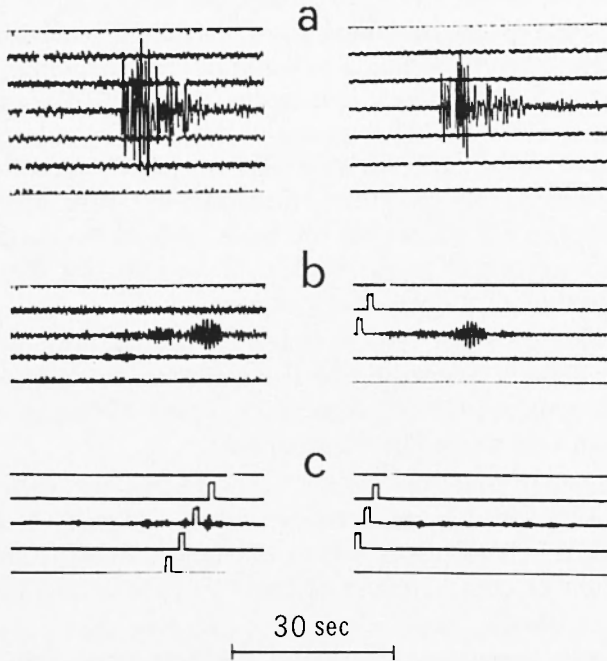


Fig. 2 - The records of two "typical" shocks (JUL 7, 1980 and AUG 10, 1980) at the Messina Strait Network are here reported: the symbols a, b, c correspond to the MES, GZ1 and 0II stations (Fig. 6), respectively. The shocks are not observed at MT1; ML1 became operative most recently.

means of the HYPOSTRE computer program (Bottari and Neri, 1980). HYPOSTRE uses the MSM crustal model and can calculate the epicenter separately from the origin time and depth. That is particularly useful above all when the number of recording times of the *P* and *S* phases is relatively low.

The results obtained using HYPOSTRE have shown the extreme superficiality ($h < 4$ km) of the events which mostly originate a little to the south of Messina (~ 10 km on average). However, even while supplying various information about some characteristics of the tectonic structures in the area (Bottari et al., 1981) the small number of events analysed has not allowed

a more complete and accurate spatial characterization of the microseismicity.

A new attempt to determine the spatial distribution of the microseismic activity is at present in course and the first results, obtained from the study of more than 30 shocks, are reported in the next section. They are then compared with those from this statistical investigation. The spatial distribution of the

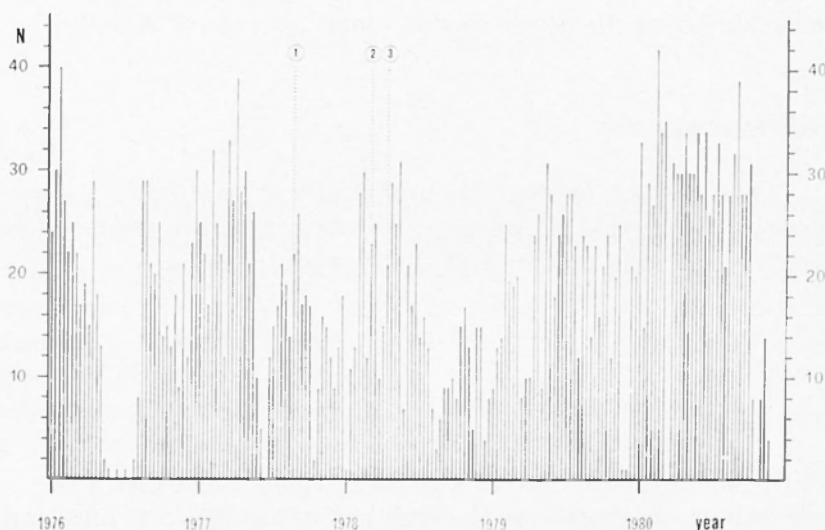


Fig. 3 - Temporal distribution of the microseismic activity during the period January 1976 - October 1980; N is the number of shocks per 10 days. The circles 1, 2 and 3 ($M > 4.5$) indicate the most energetic shocks occurred within a radius of 50 Km from MES in the same period.

seismic activity affecting a given region is, moreover, generally closely connected with the temporal distribution of the events.

The temporal pattern of the activity examined here is reported in Fig. 3 which also indicates the more intense shocks occurring in the same period within a radius of 50 km from MES. No close connection is observed between the frequency

of the microshocks on the occurrence of intermediate-energy shocks. In particular, even if an increase in microseismic activity is seen to accompany the intermediate-energy events, we observe that numerous and sometimes considerable increases in microseismic activity cannot be correlated to macroseismic events.

The period considered is 58 months in all; we have counted 3310 events, with an average of 1.87 shocks a day. The maximum number of shocks recorded in one day is nine. Some periods of inactivity of varying length (but never of more than three weeks) separate the nearly always longer periods of activity.

INDEPENDENCE TEST

As is already known, the probability $P(k, t)$ that k events occur in the period of time t is, if the events are independent, given by the relation (Poisson distribution):

$$P(k, t) = \frac{(\mu t)^k}{k!} e^{-\mu t} \quad [1]$$

where μ is the mean of the number of events per unit time interval. When intervals of one day are considered, the quantity μt , more synthetically indicated by m , is equal to the daily mean of events, and then the previous relation becomes:

$$P(k) = \frac{m^k}{k!} e^{-m} \quad [2]$$

The independence test for the events of a given set can thus be performed by comparing the experimental frequency distribution with the Poisson distribution. Various authors examine the discrepancies, between the theoretical distribution of Poisson

and the "observed" one, also by studying the $[\Delta t_i]$ series of time intervals between consecutive events (Vere-Jones and Davies, 1966; Udias and Rice, 1975) or by examining the properties of the hazard and intensity functions (Rice, 1975; Udias and Rice, 1975) or else by calculating the value of the Poisson Dispersion Coefficient D (Shlien and Toksoz, 1970; Udias and Rice, 1975). In particular, the Poisson Dispersion Coefficient (PDC) is defined by the relation:

$$D = \frac{\langle n_i^2 \rangle - \langle n_i \rangle^2}{\langle n_i \rangle^2} \quad [3]$$

where n_i is the number of events in the i -th period of assigned length Δt and the symbol $\langle \rangle$ indicates the average calculated considering all the intervals — equal to Δt — that can be extracted from the complete period to which the set of events in question refers. In the Poisson model, D is equal to 1 and therefore the difference, between the value of D determined for a certain sequence of events and 1, gives information on the level of interdependence between the events of the sequence.

The data collected in this study for the period January 1976 October 1980 lead to the histogram of Fig. 4; there one can also observe the Poisson theoretical curve offering the best fit of the experimental data. The χ^2 test confirms what is already evident from the Fig. 4 graph: the incompatibility between the Poisson model and the sequence of events in question.

Furthermore, this result is confirmed by the PDC values, obtained for Δt in the range 10-200 days (Fig. 5), and evidences the degree of interdependence between the events of the set. Here, the compatibility hypothesis is rejected when $P\chi^2 < 0.05$.

As has been previously said, the interdependence of the seismic events originating in a certain region is a fairly recurrent fact, above all if the events are superficial and if the area concerned is relatively limited. In fact, it is reasonable to maintain that the more the foci are spatially concentrated, the higher is

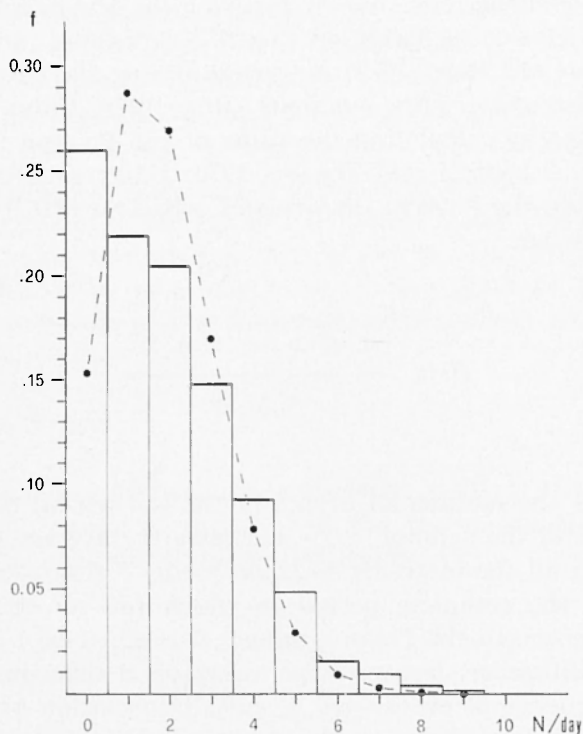


Fig. 4 - The observed frequency distribution (histogram) and that expected according to the Poisson simple model (black points) are compared: the hypothesis of independence of the shocks must be evidently rejected.

the probability that the relative events are interdependent. Therefore it can be usefully and significant to compare the results of the statistical investigation with the information collected on the spatial distribution of the activity.

The epicenters of 33 shocks belonging to the sample analysed in this study are shown in Fig. 6. They have been calculated elaborating, by a statistical criterion (paper in preparation), the arrival times of the *P* and *S* phases and the occurrence times of some subsequent impulses, which are clearly readable on the seismograms of several stations of the MSN. The majority of the

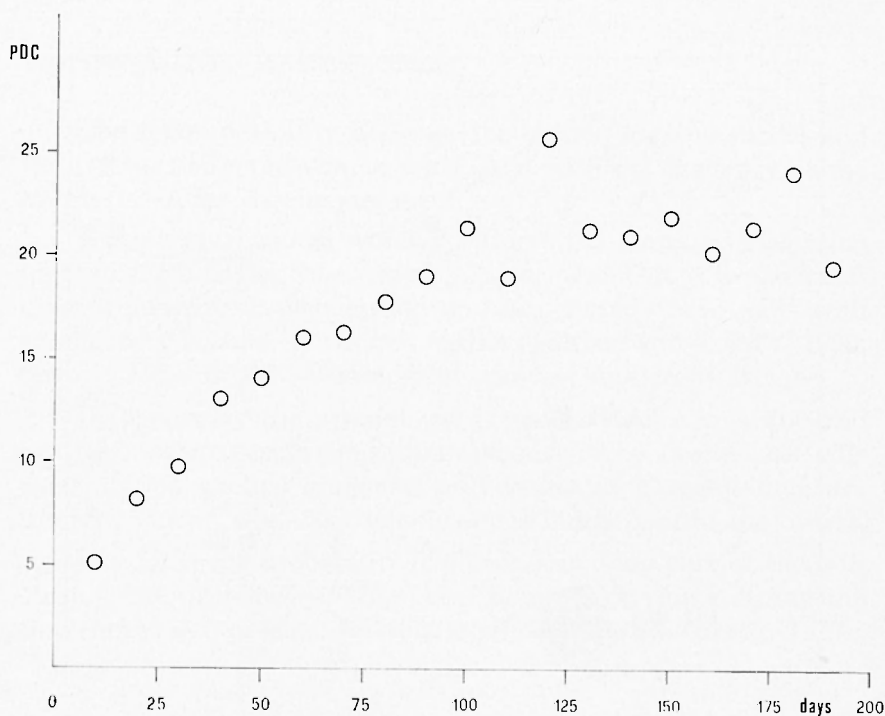


Fig. 5 - The PDC values obtained for Δt intervals in the range 10-200 days.

epicenters appear concentrated in a restricted, elliptical area (with its main axis running NW-SE) and indicate a spatial clustering phenomenon which can be well correlated with the results of the sequence analysis.

In fact, this concentration of the epicenters leads one to think that, for a great part, the events are attributable to the same structure, and this evidently explains their considerable degree of interdependence. In particular, the tendency for the activity to accumulate in bursts and the presence of prolonged periods of seismic inactivity can thereby be explained.

Further information of seismological interest and material

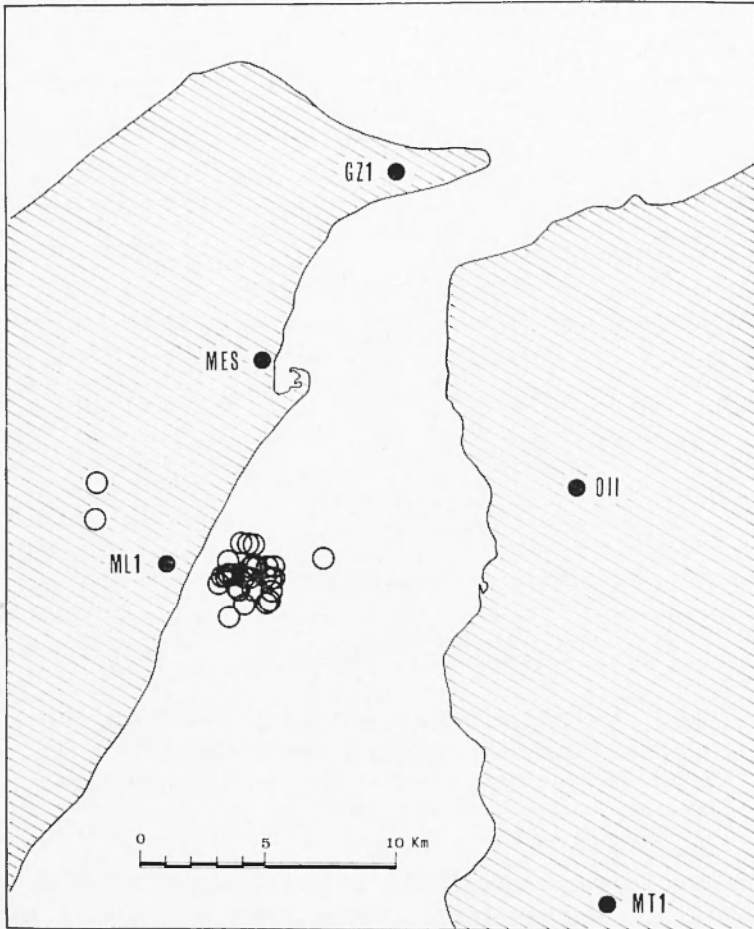


Fig. 6 - The figure shows the distribution of the epicenters (open circles) of 33 shocks belonging to the whole sample and the position of the MSN stations (black circles).

useful for a comparison with the characteristics of different areas can be had from the search for an occurrence model compatible with the observed sequence of events.

THE GENERALIZED POISSONS MODEL

The incompatibility between the simple Poisson model and the $[t_i]$ set observed can be correlated with the tendency of the events to occur in clusters.

A theoretical model which considers the temporal clustering of the events is the generalized Poisson model. It is a particular case of compound distribution and has already been used with satisfactory results by various authors (Shlien and Toksöz, 1970; Savage, 1972) in the seismological study of numerous areas.

In particular the generalized Poisson model allows for two or more events occurring simultaneously; the events are concentrated in groups (clusters) and inside each group they are interdependent, whereas each cluster is independent of the others.

If $q(j)$ is the probability of j events making part of the n -th cluster, the probability $P_q(k, t)$ that k events originate during the time interval t is given by relations (Shlien and Toksöz, 1970):

$$p_q(k, t) = e^{-k't} , \quad \text{if } k = 0 \quad [4]$$

$$p_q(k, t) = \frac{k't}{k} \sum_{j=0}^n (k-j) q(k-j) p_q(j, t), \quad \text{if } k > 0 \quad [5]$$

the variable n is equal to $k-1$; $k't$ is the average number of clusters occurring in the time interval t . The previous relations are deducible from the more general formula, valid for compound distributions, by imposing the condition of independence of the clusters.

Evidently, the use of relations [4] and [5] to fit the observed frequency distribution presupposes some assumptions about the analytical form to be attributed to the function $q(n)$. The choice of this function can come from an analysis of the sequence in question, attempting to identify the clusters, or from a preli-

minary calculation of the coefficients $q(n)$ by means of the same relations [4] and [5] after substituting in them for P_q the observed frequency values.

Following this last criterion, the results obtained have led us to consider a $q(n)$ distribution of the Pareto type:

$$q(n) = \frac{1}{\zeta(E)} n^{-E}$$

where $\zeta(E)$ is the Riemann Z function:

$$\zeta(E) = \sum_{m=1}^{\infty} \frac{1}{m^E}$$

The calculation of the values of k' and E corresponding to the best fit of the experimental data — possible by means of [4] and [5] — was done by the maximum likelihood method and gave the results:

$$k' = 1.6 \quad \text{and} \quad E = 3.4$$

which are close to those obtained, using an analogous methodology, by Shlien and Toksöz in the study of areas of continental extension and by Savage for the region of Fairview Peak (Nevada).

The χ^2 test shows that the compound Poisson distribution fits the observational data decidedly better than does the simple Poisson distribution: nevertheless there is still considerable disagreement between the expected frequencies and those observed. This discrepancy also observed in other areas, is examined and interpreted.

In our case, we do not consider it can be attributed exclusively to incompleteness factors of the $[t_i]$ set examined. In fact, a comparison of the experimental histogram and the theoretical frequencies (Fig. 7) calls attention to the high number of periods of inactivity which, as has already been pointed out, are present in the sample period.

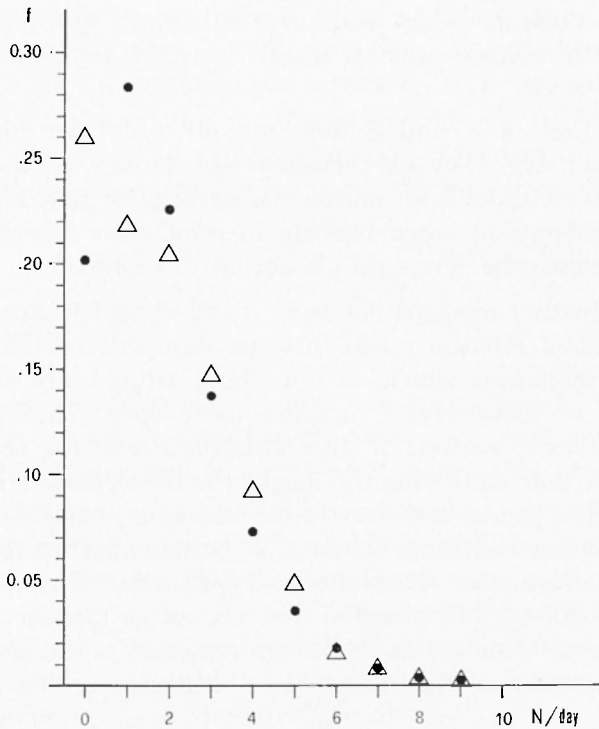


Fig. 7 - The figure shows the observed frequency distribution (triangles) and that expected according to the generalized Poisson model (black points). The disagreement is less than in the case of Poisson simple fit; nevertheless it is not still negligible.

A series of attempts, made by subtracting from the whole sample all those periods of inactivity longer than x days, indicates that the adherence between the generalized Poisson model

and the observational data increase as x decreases, until reaching satisfactory levels for $x < 4$. In particular, the results obtained show that χ^2 is minimum when $x = 2$, and in that case its value (7.6) is consistently smaller than $\chi^2_{0.95}$ (15.5).

This result proves that the temporal distribution of the microseismicity originating near Messina can be represented as a series of "activity" periods — on the average conforming with a compound Poisson model with $q(n)$ of the Pareto type — separated by intervals of seismic inactivity which never last longer than three weeks.

The values of k' and E obtained for $x < 4$ are close to 2 and 4 respectively. They are therefore higher than those obtained (1.6 and 3.4) without subtracting the periods of inactivity; that is easily understood when bearing in mind that this operation tends to reduce the temporal clustering phenomenon.

Yet a further analysis has been made to verify directly how the generalized Poisson model fits the data relative to each of the single sequences which, in the whole sample, are separated by periods of inactivity of at least three days. The single sequences refers to periods of different length and the results obtained show that increasing the length the discrepancies between the theoretical model and the experimental frequencies decrease. A period lasting less than 100 days is statistically insufficient to show the tendency of the events to be distributed according to compound Poisson distribution: on the other hand, when the length is more than 300 days, the discrepancies are considerably more contained and the sample can be considered statistically significant.

There is another aspect of the problem that deserves attention. We have already emphasized the periods of seismic inactivity lasting excessively long compared with what is predictable on the basis of the generalized Poisson model. It seems right to suppose that the higher is the number of active structures in a given area and the more they can be considered independent of one another, the less probable is it that the periods of inactivity will be long. That, considering also the mean rate of activity observed in the area under study, suggests the hypothesis, one

furthermore in agreement with the results of the epicentral calculation of the shocks (cf. preceding section), that the microseismicity here examined is attributable to a single structure, or at the most to very few closely interdependent structures.

Further investigations of the microseismicity near Messina are now being made. In particular, a search for possible periodicities of the phenomenon and for possible correlations with external factors is being made in order to enlarge the information available and to offer a more complete characterization of the structures giving origin to the activity.

In our opinion, the content of the present paper is a valid point of departure to achieve the final objective: the definition of a reliable dynamic model for the active structures of the Strait of Messina.

CONCLUSIONS

The statistical analysis applied to a sequence of 3310 microshocks, recorded at the Messina University station in the last five years, gives a significant picture of the same activity.

The Poisson simple model is inadequate to describe the temporal distribution of the events, which show the tendency to group in clusters; the χ^2 and PDC (Poisson Dispersion Coefficient) values indicate, in fact, a considerable interdependence of the shocks. This result seems to be well correlated with those from an analysis of the spatial distribution of the activity which presents an evident phenomenon of spatial clustering.

The generalized Poisson model gives a better — but still unsatisfactory — approximation of the observed frequency distribution; the residual disagreement is due to the high number of periods of inactivity which are present in the whole sample.

In fact, a series of attempts, made by subtracting from the sample all those periods of inactivity longer than x days, indicates that $\chi^2 < \chi^2_{0.95}$ when $x < 4$. In particular, it is minimum (7.6; $\chi^2_{0.95} = 15.5$) when $x = 2$. This result proves that the sequence can be represented as a succession of periods of activity — "on

the average" conforming with a compound Poisson model — separated by interval of seismic inactivity which never last longer than three weeks.

A further analysis, made to verify directly how the generalized Poisson model fits the data relative to each of the single sequences separated by intervals of inactivity, indicates the goodness of the fit when the length of the period exceeds 300 days. Generally, a period lasting less than 300 days is statistically insufficient to show the tendency of the events to be distributed according to a compound Poisson distribution.

The results obtained and the length of the periods of inactivity suggest the hypothesis, one furthermore in agreement with the results of the epicentral calculations, that the microseismicity originating near Messina can be attributed to a single structure or at the most to very few closely interdependent structures.

Finally, no close connection is observed between the frequency of the microshocks and the occurrence of intermediate-energy shocks in the same region.

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