On locating local earthquakes at the Messina Strait network

A. BOTTARI - G. NERI

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ABSTRACT

A computer program (HYPOSTRE) has been elaborated to determine the hypocentral parameters of local earthquakes, even when they are recorded by a small number of stations. These are the most frequent conditions prevailing around the Strait of Messina.

The program employs the first arrivals of *P* and *S* waves, a model of local crust consisting of four plane and parallel layers, and an algorithm based on that of Geiger.

HYPOSTRE can determine simultaneously the four unknowns λ, φ, h and H (HYPOSTRE 4) and can calculate the epicentral coordinate separately from focal depth (HYPOSTRE 2). In both cases the program follows an iterative process. In particular, HYPOSTRE 2 shows convergence towards a final solution, through a series of « damped » approximations.

The application of HYPOSTRE to about twenty earthquakes, which have occured in the Strait of Messina and in the Gulf of Patti, demonstrates a good convergence and a general stability of results.

Finally, comparison with analogous determinations — carried out by other programs, with different crustal models and using a greater number of recorded data — confirms the reliability of HYPOSTRE.

Riassunto

E' stato elaborato un programma per il calcolatore (Hypostre) destinato a determinare i parametri ipocentrali di terremoti locali, sempreché siano stati registrati da un certo numero di stazioni. Queste sono le condizioni più frequenti esistenti nei dintorni dello Stretto di Messina.

Il programma utilizza i primi arrivi delle onde *P* ed *S*, un modello di crosta locale consistente di quattro strati piatti e paralleli, ed un algoritmo basato su quello di Geiger.

Hypostre può determinare contemporaneamente le quattro incognite λ, φ, h e H (Hypostre 4) ed è in grado di calcolare le coordinate epicentrali separatamente dalla profondità ipocentrale (Hypostre 2). In entrambi i casi il programma segue un processo iterativo. In particolare, Hypostre 2 mostra convergenza verso una soluzione finale attraverso una serie di approssimazioni « smorzate ».

L'applicazione di Hypostre a circa 20 terremoti, occorsi nello Stretto di Messina e nel Golfo di Patti, dimostra una buona convergenza ed una stabilità generale di risultati.

Infine, un confronto con determinazioni analoghe — elaborate per mezzo di altri programmi, con differenti modelli crostali ed usando un maggior numero di dati di registrazione —, conferma l'attendibilità di Hypostre.

Introduction

For over a decade the problem of determining hypocentral coordinates, using seismic data only from those stations near the epicenter, has received particular attention.

Such an approach is related to the conspicuous number of local seismic networks set up in various regions for studying seismic areas of particular interest; it is also strictly connected with study methodology (Bolt, 1960; Nordquist, 1962; James et al., 1969; Kondorskaya et al., 1978).

This approach leads to some difficulties: the number of stations used in the calculation and their siting with respect to the epicenter are not always satisfactory and the algorithm employed for the determination is therefore, for these reasons too, unsuitable. Generally problems of convergence regarding the calculation process arise: various authors (Buland, 1976; Lomnitz,

1977) propose new algorithms in order to guarantee a greater stability of results and also suggest, as do others (Engdahl and Gunst, 1966; Bottari et al., 1975; Kondorskaya et al., 1978), the determination of the epicentral coordinates separately from the depth.

James et al. (1969) advise the preliminary determination of origin time and then the calculation of latitude, longitude and depth, realizing that the cause of limitation of the statistical process generally adopted is the interdependence between origin time and spatial coordinates.

The variety of methods suggested in the literature must be seen in relation to the heterogeneity of problems and situations connected with seismological studies of different regions. The network geometry and the level of knowledge regarding the crustal structure of the studied regions can in fact favor the use of particular methods rather than of others. For example, the method proposed by Crosson (1976), for simultaneous determination of the hypocentral parameters and of the velocity model in the focal area,is of particular use above all in regions where there is little satisfactory knowledge regarding the propagative characteristics of seismic waves inside the crust.

The HYPOSTRE Program

The HYPOSTRE program, elaborated ad hoc for use by the Messina Strait Network (MSN), is derived from a well known hypocentral determination method (Geiger, 1910), adapted to the case of a plane crust with parallel and isotropic layers.

The method is based on the system of condition equations:

$$\delta H_o + \frac{\partial f_i}{\partial \lambda_o} \delta\lambda_o + \frac{\partial f_i}{\partial \varphi_o} \delta\varphi_o + \frac{\partial f_i}{\partial h_o} \delta h_o + e_i = 0$$

$$(i = 1, 2, \ldots, N)$$

where

$e_i = -\{ t_i - [H_o + f_i(\lambda_o, \varphi_o, h_o)\}$ is the residual time.

of a generic station. The symbols H_o, λ_o, φ_o, h_o represent the preliminary focal parameters, the function $f(\lambda, \varphi, h)$ is the travel-time of the phase which arrives at the i-th station at time t_i and δH_o, $\delta\lambda_o$, $\delta\varphi_o$, δh_o are the quantities to be added to H_o, λ_o, φ_o and h_o to obtain the « corrected » hypocentral coordinates H, λ, φ, and h.

In our case, if X and Y represent the longitude and latitude in a cartesian coordinate system, the equations can be written as follows:

$$\partial H_o + \frac{\partial f_i}{\partial X_o} \delta X_o + \frac{\partial f_i}{\partial Y} \delta Y_o + \frac{\partial f_i}{\partial h_o} \delta h_o + l_i = 0$$

The « standars » travel-times for the first arrivals employed in the calculation are those compatible with a crustal model recently suggested for the area surrounding the Strait of Messina (Bottari et al., 1979). In order to have, for the calculation, a large account of data, including those from neighbouring networks, the local model (Messina Strait Model, MSM), for $D > 70$ km, has been attached to that of Jeffreys and Bullen (1967).

The MSM travel-times are memorized on file at intervals of 1 km for both distance and depth.

Furthermore, a routine which carries out the calculation of S phase travel-times, for the different distances and depths, has been introduced into the program. This allows the arrival times observed for the S phase to be used.

HYPOSTRE can calculate simultaneously the four focal parameters (HYPOSTRE 4), or determine the epicenter separately from the depth (HYPOSTRE 2). Generally HYPOSTRE 2 — which operates in two stages « a » and « b » — carries out the calculation more rapidly than HYPOSTRE 4 and guarantees a greater stability of results. This is very justifiable considering the application limits of a statistic method to a relatively small set of data. The condition $N \gg 4$ is, in fact, rarely found.

In the first stage (a), HYPOSTRE, for each h value belonging to a fixed set of hypocentral depths, calculates the triad λ, φ, H, which minimize the residual square sum $\sum_i e^2_i$. The correct epicenter is the one corresponding to the minimum standard deviation, regardless of the value of h used. This, satisfying a general principle of statistics, allows one to verify the relatively slight dependence of the epicentral site on the h value used; it also allows one to evaluate if the stations are well sited around the focus and the congruence of the observed times.

The values of λ and φ obtained in the above stage are employed in the following stage, relative to the calculation of depth and origin time. In this stage HYPOSTRE 2 operates using a set S (h_i) of preliminary values for the depth: for each h_1, an iteration cycle is carried out and this leads to a final value for the hypocentral depth.

For each h_i, the computer carries out the following operations:

1. Reads the value given to the variable which indicates the required procedure (with the four free parameters, whith a given depth or with fixed latitude and longitude).

2. Reads the provisional focal parameters, the geographical coordinates of the stations and the arrival times of the P and S waves.

3. Calculates the epicenter-station distances, the observed times, those foreseen according to the model and the residual times.

4. Determines the coefficients of the condition equations for both P and S waves giving a relative weight.

5. Solves the system with the least-square method and corrects the focal parameters.

6. Prints the corrected focal coordinates and the uncertainties of the results.

7. Goes back immediately to step 3 — if a given number of iterations has not yet been carried out — for a new cycle with uses the results of the previous cycle as preliminary values.

Once the correction has been made, the interruption of the calculation occurs, however, when the depth of the focus or at least one of the epicentral distances exceeds the validity limits of the model.

HYPOSTRE, written in FORTRAN IV, for an IBM 370, occupies 25K of memory and, with this computer, takes just over a second for each iteration.

Application and comparison

In order to test HYPOSTRE, the program has been used to determine the focal parameters of two somewhat different seismic events. In fact, the most intensive earthquake during the last two years within the region where the model is valid, and a low-energy shock originating in the Strait of Messina, have been studied.

With regard to the intensive earthquake of 16.4.1978, the test is based on a comparison of the λ, φ, h and H values with those from other calculation programs employing different velocity models, and on the evaluation of the solution stability. For the shock originating in the Strait, only an evaluation of the solution stability is possible as, due to the low-energy of the event, there are no determinations from other programs.

The results obtained in both events using data from about ten stations, are shown in Table I, where are also indicated, in brackets, the focal parameters of the Patti earthquake, calculated by the Istituto Nazionale di Geofisica (I.N.G., Rome).

This first test already gives a positive indication of the procedure convergence and of the solution stability; in fact, for both the studied events, one observes:

i) an excellent clustering of the epicenters determined in stage « a » in relation to different depth values (Figs. 1a and 1b);

ii) the independence of the results obtained in the latitude and longitude calculation from the preliminary position of the epicenter (Figs. 2a and 2b);

iii) the independence of the calculated depth value from the provisional one (Figs. 3a and 3b).

In order to obtain further proof of the HYPOSTRE properties and, thus, of the suitability of the velocity model employed, the four focal parameters of 14 other earthquakes originating in the Gulf of Patti, covering a period from April 1978 to June 1979, have been determined. The choice of the events (those having a magnitude greater than 4 and some with $M > 3.5$) has generally allowed the use of at least ten observed times for P and S waves. The results are reported in Table II.

The new test has confirmed the convergence properties already shown by HYPOSTRE: the solution instability and the dependence of this on the preliminary values have been observed only in a few cases. However, a reliable estimate of the solutions has always been possible (see the following section).

TABLE I

Earthquake	M	Origin Time hr min sec	Latitude deg min sec	Longitude deg min sec	Depth Km
Gulf of Patti 15 APR 78	5.5	23 33 47.4	38 18 24.9	15 03 39.3	24.7
		(23 33 47.4)	(38 16 04.8)	(15 06 43.2)	(22.0)
Strait of Messina 03 AUG 769	2.3	04 09 25.3	38 09 15.1	15 32 35.4	8.0

The epicenters obtained by HYPOSTRE for the 15 earthquakes occuring in the Gulf of Patti are represented in Fig. 4 by shaded circles; in the same figure, the epicenters published by the I.N.G. are shown in plain circles.

The HYPOSTRE epicenters seem considerably less dispersed with respect to the others and moreover their alignment in NW-SE direction is evident. The last circumstance supports the

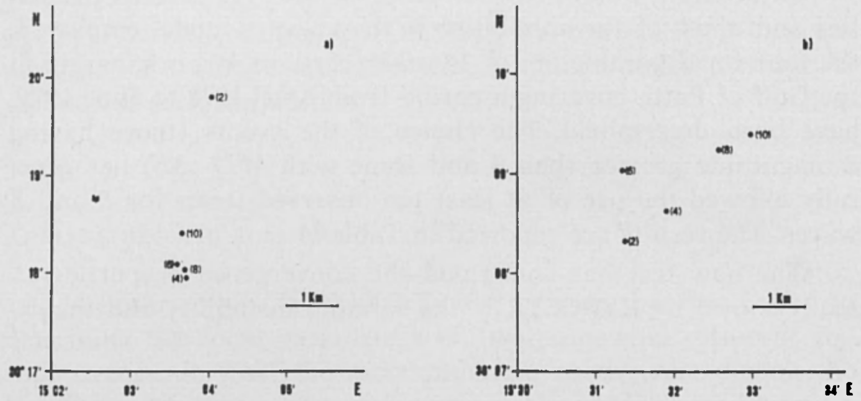

Fig. 1 - The epicenters determined in the first stage of the calculation in relation to different depth values, for the earthquake of the Gulf of Patti (a) and for the shock of the Messina Strait (b).

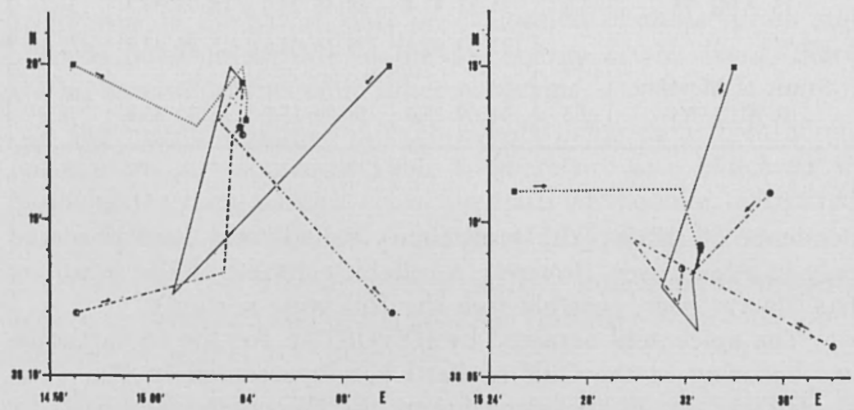

Fig. 2 - The figure shows the independence of the calculated epicenter from the preliminary position attributed to it.

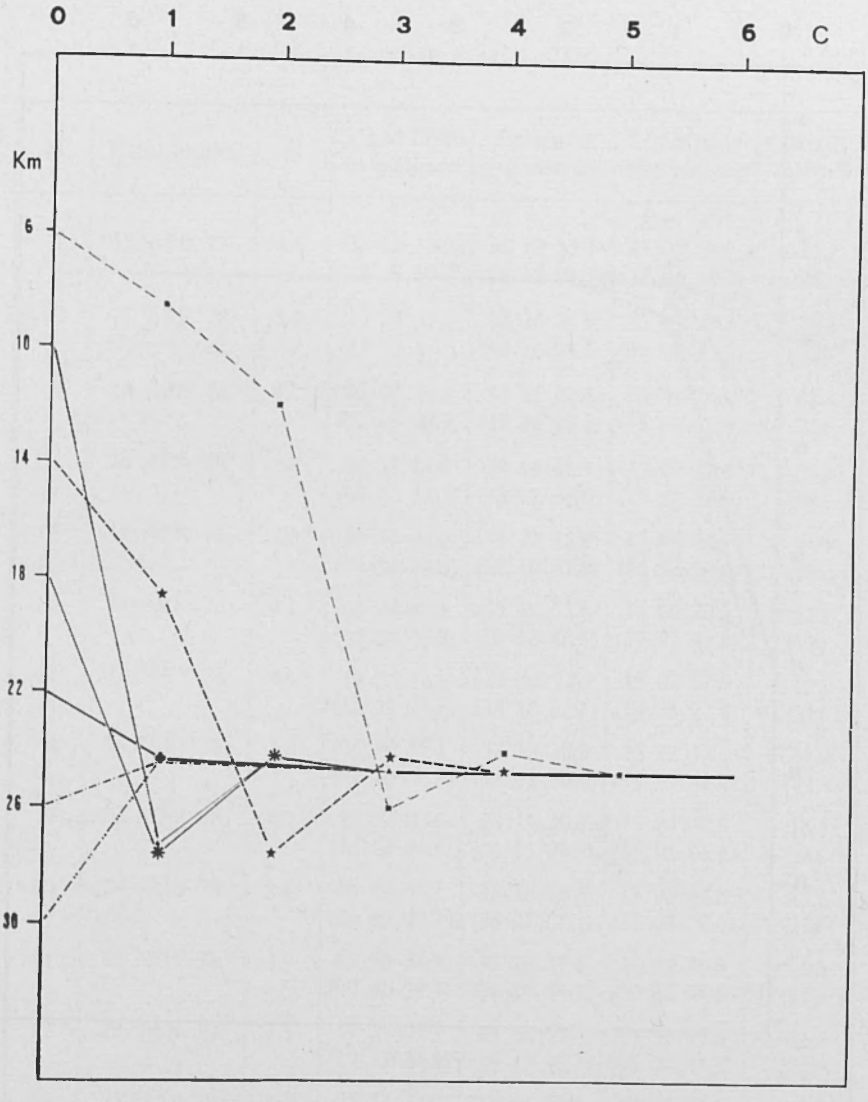

Fig. 3 a, b - The depth values obtained in the calculation for each iteration and the good convergence of h to a definitive value.

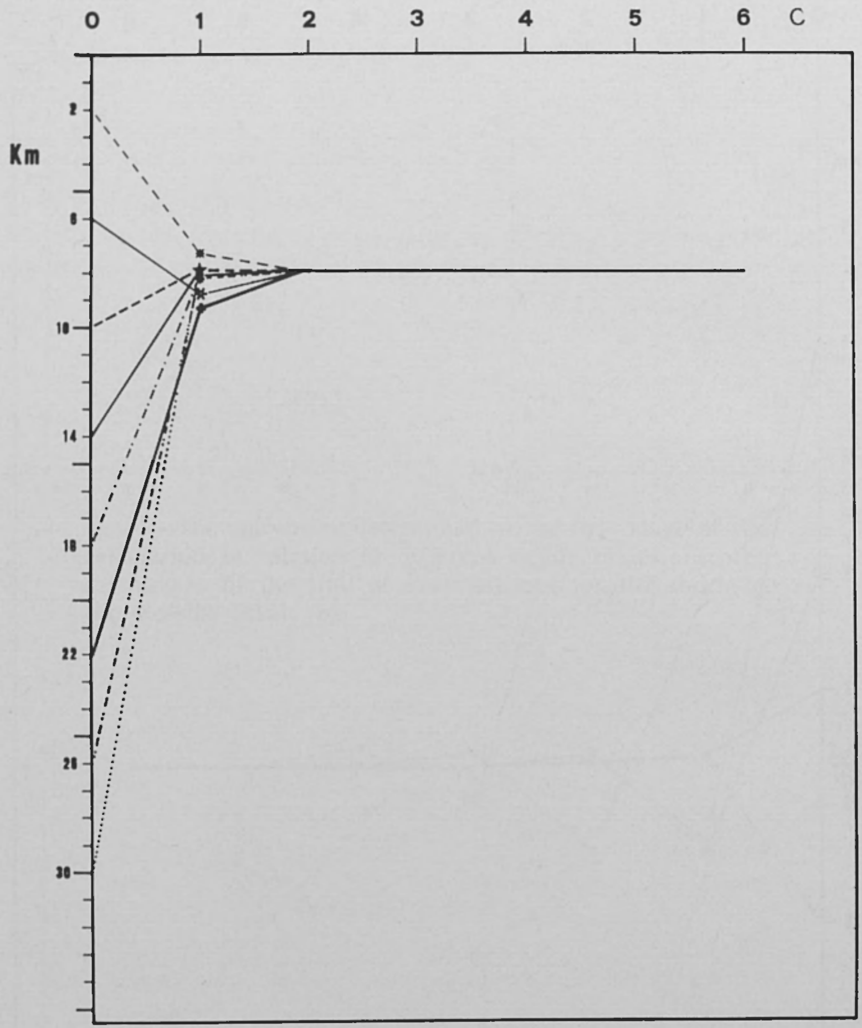

Fig. 3 b

TABLE II

N	Earthquake	*M*	Origin Time hr min sec	Latitude deg min sec	Longitude deg min sec	Depth Km
1	15 APR 78	4.4	23 29 10.9 (23 29 10.7)	38 19 35.0 (38 20 06.0)	15 05 36.3 (15 05 31.2)	23.1 (23)
2	15 APR 78 Main Shock	5.5	23 33 47.4 (23 33 47.4)	38 18 24.9 (38 16 04.8)	15 03 39.3 (15 06 43.2)	24.7 (22)
3	16 APR 78	4.1	02 04 30.4 (02 04 29.5)	38 21 40.8 (38 24 18.0)	15 01 36.0 (15 02 16.8)	11.1 (21)
4	16 APR 78	3.8	04 38 14.0 (04 38 13.2)	38 16 41.9 (38 21 36.0)	15 02 12.5 (15 05 16.8)	27.8 (38)
5	16 APR 78	4.0	14 34 44.0 (14 34 44.0)	38 22 32.8 (38 18 57.6)	15 00 58.7 (14 57 00.0)	14.1 (11)
6	24 APR 78	4.1	03 34 01.5 (03 34 01.4)	38 19 53.8 (38 18 46.8)	15 00 20.5 (14 57 46.8)	11.1 (12)
7	10 MAY 78	4.0	18 51 14.6 (18 51 13.7)	38 15 12.1 (38 10 58.8)	15 02 57.6 (14 58 22.8)	10.1 (21)
8	11 MAY 78	4.2	02 46 57.1 (02 46 56.9)	38 15 38.0 (38 12 50.4)	15 02 12.5 (14 59 42.0)	22.9 (22)
9	03 JUN 78	4.2	13 52 07.6 (13 52 06.9)	38 14 10.4 (38 15 03.6)	15 04 49.3 (15 03 03.6)	18.5 (33)
10	24 AUG 78	3.8	04 58 48.1 (04 58 47.9)	38 18 56.6 (38 21 07.2)	15 02 43.6 (15 03 21.6)	15.3 (21)
11	25 NOV 78	3.9	09 45 34.9 (09 45 34.4)	38 19 17.8 (38 20 49.2)	15 02 36.6 (15 04 04.8)	16.5 (22)
12	25 JAN 79	4.3	19 27 09.1 (19 27 08.9)	38 14 33.4 (38 17 49.2)	14 59 48.0 (15 02 16.8)	02.0 (22)
13	23 MAR 79	3.7	05 32 23.0 (05 32 23.2)	38 16 50.2 (38 15 36.0)	15 02 35.6 (15 01 55.2)	11.9 (06)
14	03 JUN 79	4.0	14 57 47.3 (14 57 46.9)	38 12 37.1 (38 12 50.4)	15 04 18.6 (15 01 40.8)	02.9 (20)
15	05 JUN 78	4.1	11 44 21.6 (11 44 21.3)	38 18 03.8 (38 20 06.0)	14 56 28.5 (14 52 12.0)	11.7 (19)

TABLE III

Preliminary Depth Km	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
2.0	12.6	13.5	16.1	16.6	16.6	16.6
6.0	14.2	15.0	15.3	15.3	15.3	15.3
10.0	19.3	15.5	15.3	15.3	15.3	15.3
14.0	15.0	15.3	15.3	15.3	15.3	15.3
18.0	15.3	15.3	15.3	15.3	15.3	15.3
22.0	17.4	15.7	15.3	15.3	15.3	15.3
26.0	16.6	16.6	16.6	16.6	16.6	16.6
30.0	17.1	15.7	15.3	15.3	15.3	15.3

TABLE IV

Preliminary Depth Km	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
2.0	11.2	12.8	11.1	12.8	11.1	12.8
6.0	8.6	12.9	11.1	12.8	11.1	12.8
10.0	13.6	11.2	12.8	11.1	12.8	11.1
14.0	10.7	13.6	11.2	12.8	11.1	12.8
18.0	10.9	13.6	11.2	12.8	11.1	12.8
22.0	13.6	11.2	12.8	11.1	12.8	11.1
26.0	12.2	11.1	12.8	11.1	12.8	11.1
30.0	11.4	12.8	11.1	12.8	11.1	12.8

reasoning of various authors on the geo-structural inmplications of the earthquakes around the Gulf of Patti.

This emphasizes the characteristics of our calculation procedure which employs an adequate velocity model and gives satisfactory results even when using a small number of data.

LIMITS OF APPLICABILITY

In the previous section the few cases have been referred to in which HYPOSTRE gives solutions that are instable or that depend on the preliminary values.

Therefore, the results of the depth calculation for two of the earthquakes previously analyzed are reported, step by step, in Table III and IV.

As can be seen, for the earthquake of 24.8.1978 ($M = 3.8$), the depth converges towards either 15.3 or 16.6 km, according to the preliminary value given to it; instead, for the event of 16.4.78 ($M = 4.1$), the depth initially converges towards the value of 11.1 km but after oscillates between 11.1 and 12.8 km. In both cases it is however possible to give a definitive reliable value to the depth if one considers that the difference between the two values (15.3 and 16.6 in the first case; 11.1 and 12.8 in the second) is fairly small with respect to the probable extension of the focal area.

Finally, the analysis of all the results obtained studying the earthquakes of the Gulf of Patti and of the results from about ten other determinations, carried out for low-energy events ($M < 2.5$) originating in the Strait of Messina, allows us to recognize that the distribution of stations and the quality of the observed data are very important elements for the stability. In particular, the determinations carried out using the data from only the MSN stations, for shocks originating in the Strait, do not generally present problems of convergence and of stability. In fact, for such events the siting of the MSN stations (Fig. 4), with regard to azimuth and epicentral distance, is generally enough to compensate the effects of instability which can derive from the « interaction » between the algorithm and the travel-times employed.

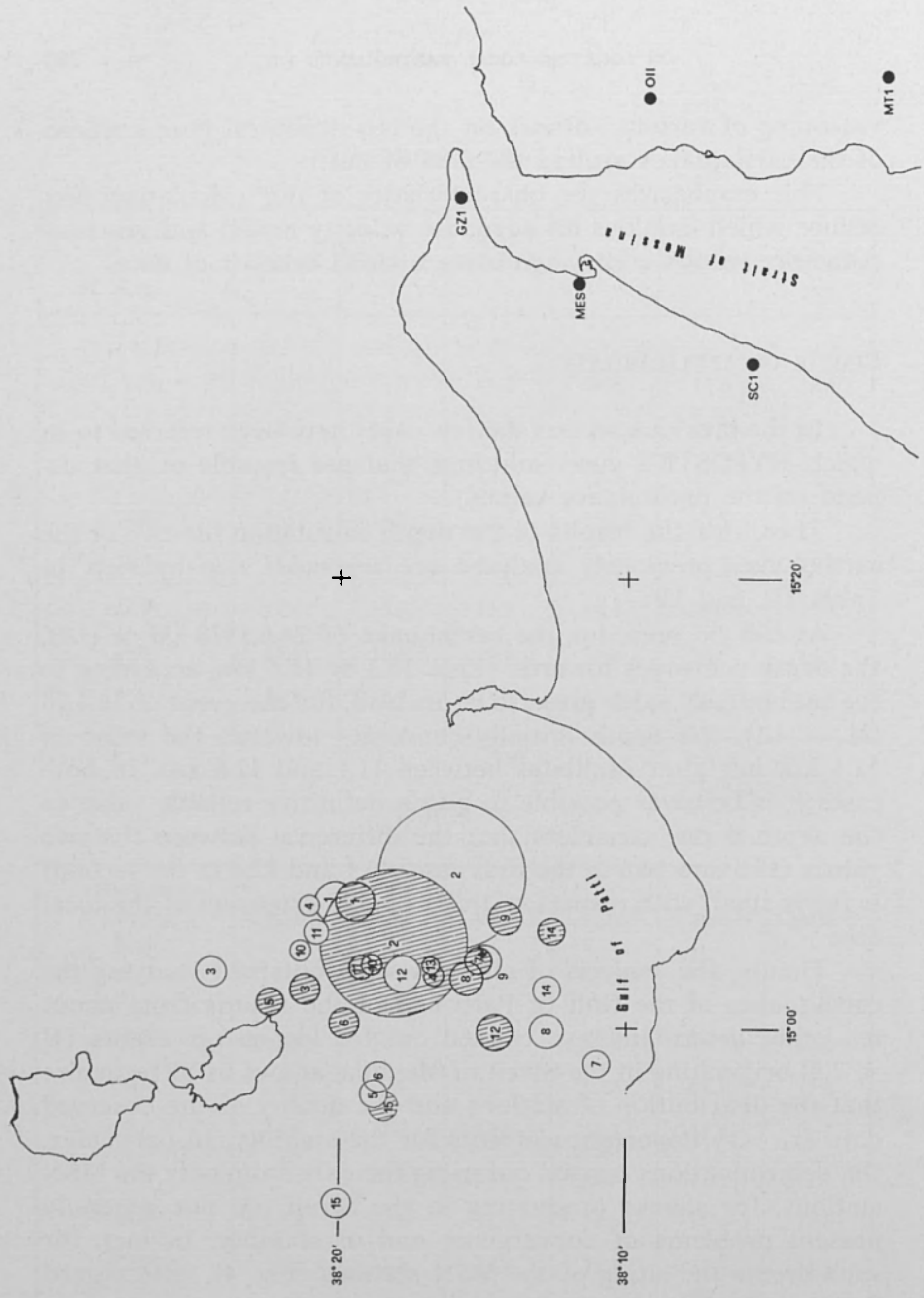

Fig. 4 - The HYPOSTRE (shaded circles) and I.N.G. (plain circles) epicenters obtained for 15 earthquakes in the Gull of Patti and the siting of the MSN stations.

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