SEISMIC MONITORING IN ITALIAN GEOTHERMAL AREAS
I. SEISMIC ACTIVITY IN THE LARDERELLO TRAVALE REGION

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1. INTRODUCTION

Natural seismic activity, characteristic of geothermal fields, may be modified when changes in the fluid-thermodynamic conditions occur in the subsoil, brought about by production and re-injection of fluids. In fact, it has been seen that faults may vary their degree of seismic activity if the pressure of fluids is modified in tectonically active areas and that shallow earthquakes can be generated by a subsequent reduction of the "effective normal stress" (Healy et al. 1968; Teng et al. 1973; Raleigh et al. 1972). In order to measure the effects of variations in the pore pressure on natural seismic activity, a seismic network was installed about four years ago in the Larderello Travale geothermal region and in this report we will discuss the results obtained during the period extending from March 1977 to June 1980.

2. GEOLOGICAL-STRUCTURAL DESCRIPTION OF THE LARDERELLO-TRAVALE REGION

A geological-structural description of the Boraciferous Region has been given in detail by various authors (Lazarotti, 1967; Mazzanti, 1966; Cataldi et al. 1963; Giannini et al., 1970; Batini et al. 1978). The outcropping terrains may be grouped under the following complexes, in order of succession from top to bottom:

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1) Neoautocton: consisting of lacustrine and marine and lagoon deposits of the Upper Miocene and Pliocenic marine sediments which are predominantly clayey. It transgresses into almost all of the units below.

2) Nappes of "Liguridi" (a.s.l.): to these belong formations in flysch "facies" and ofiolites of Cretaceous to Eocene age. This unit lies on the tectonic units described below.

3) Tuscan Nappes: this is the well-known Triassic-Oligocenic sequence with predominantly carbonate mesozoic formations in the basal part and terrigenous formations from Cretaceous to Oligocene in the upper part. This tectonic unit is frequently present with an incomplete sequence or with only the "Burano" anhydrite formation. The latter, connected to dolomite and anhydrite breccias, forms the base of the unit. In some areas, the "Tuscan Nappes" are totally absent. Tectonic wedges are present between the Tuscan Nappes and the regional basement mainly in correspondence of Castelnuovo-Larderello and Serrazzano area.

4) "Basement": these formations are present in the upper part of quartzites and phyllites attributed to the pre-carboniferous. In the lower part (over 3000 meters deep) we find mica-schists and gneiss formations. All these tectonic units lie in conformity on a surface of discontinuity which, at a depth of about 4-5 km, has been detected by means of seismic reflection prospecting.

The tectonic is characterized by two styles:

- the first being plicative, has determined a series of folds generally oriented in an appennine direction with an axial dipping toward NW;
- the second being rigid, has led to the formation of a series of faults which cut the folded structures which have previously formed in different directions. The prevailing directions are appennine (NW-SE) and anti-appennine (NE-SW) (Fig. 1).

The structural situation created at the end of the tectonic movements described is represented by "horst" and "graben" structures; the latter have for the most part given rise to sedimentation basins, during the marine invasion of the Miocene and the Pliocene.

3. SEISMOGRAPHIC COVERAGE

Seismographic monitoring in the Larderello-Travale geothermal region was begun in June 1976 with the installation of three permanent seismographic stations (CLSE; NINI and SDAL). Subsequently, seismographic coverage has been increased (Fig. 2), but new stations will have to be set up in order to better control seismic activity in the Larderello-Travale geothermal region which is currently being explored and exploited. Each station consists of a seismometer type Willmore MXIII A/S of 1 sec period and with the generator's constant average > 450 V/m/sec.

The seismic signal, amplified and frequency modulated, is transmitted via radio to multi-channel analogic magnetic tape recorder which records signals with a maximum frequency of 16 Hz.

4. Data Analysis

The determination of the focal co-ordinates of the seismic events recorded by the network is done by means of the Hypoellipse program (Lahr, 1979) based on a model of layered earth which differs from one

SEISMIC MONITORING IN ITALIAN GEOTHERMAL AREAS (1st part)

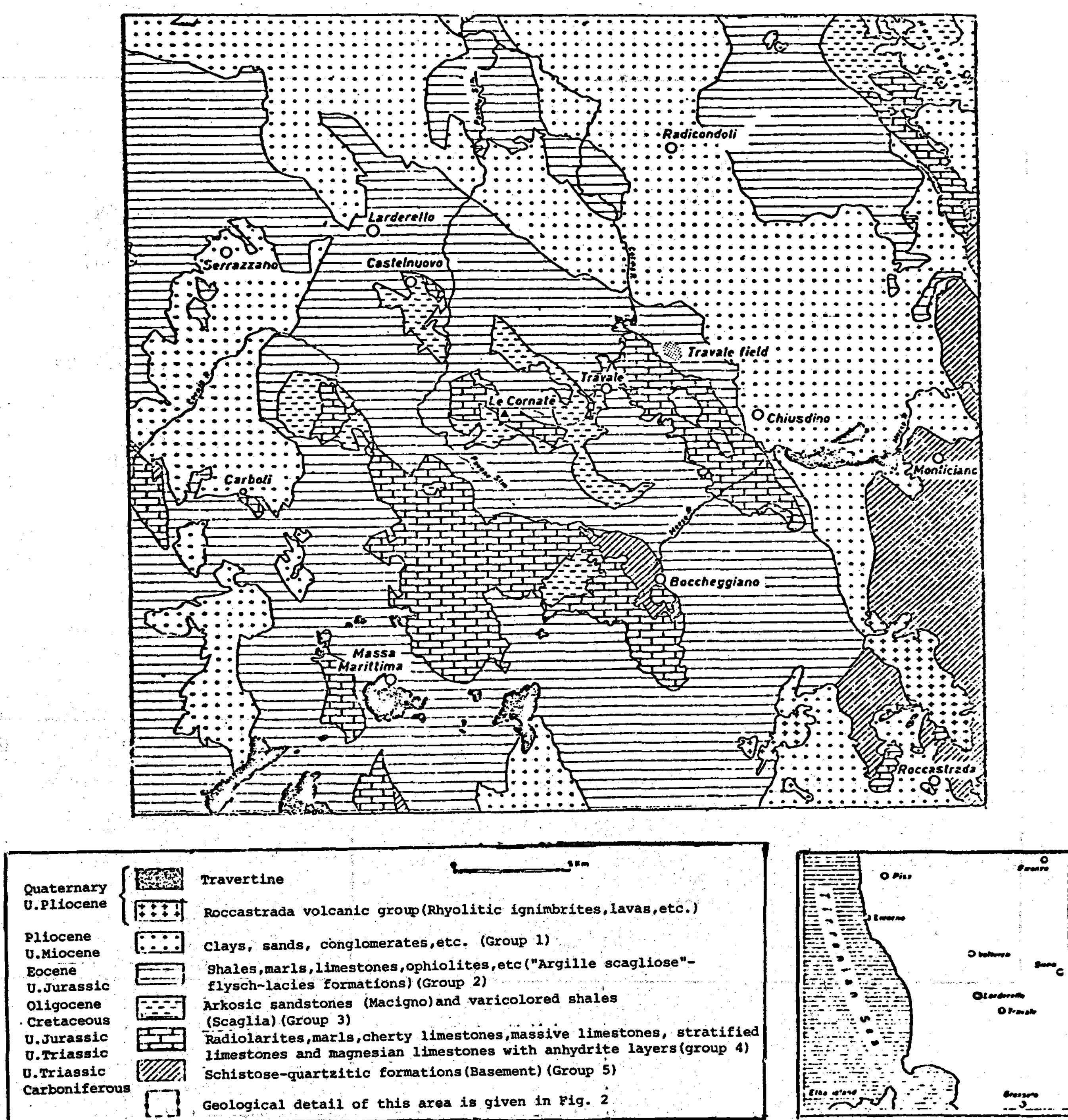


Fig. 1. Location and schematic geological map of the Larderello-Travale region.

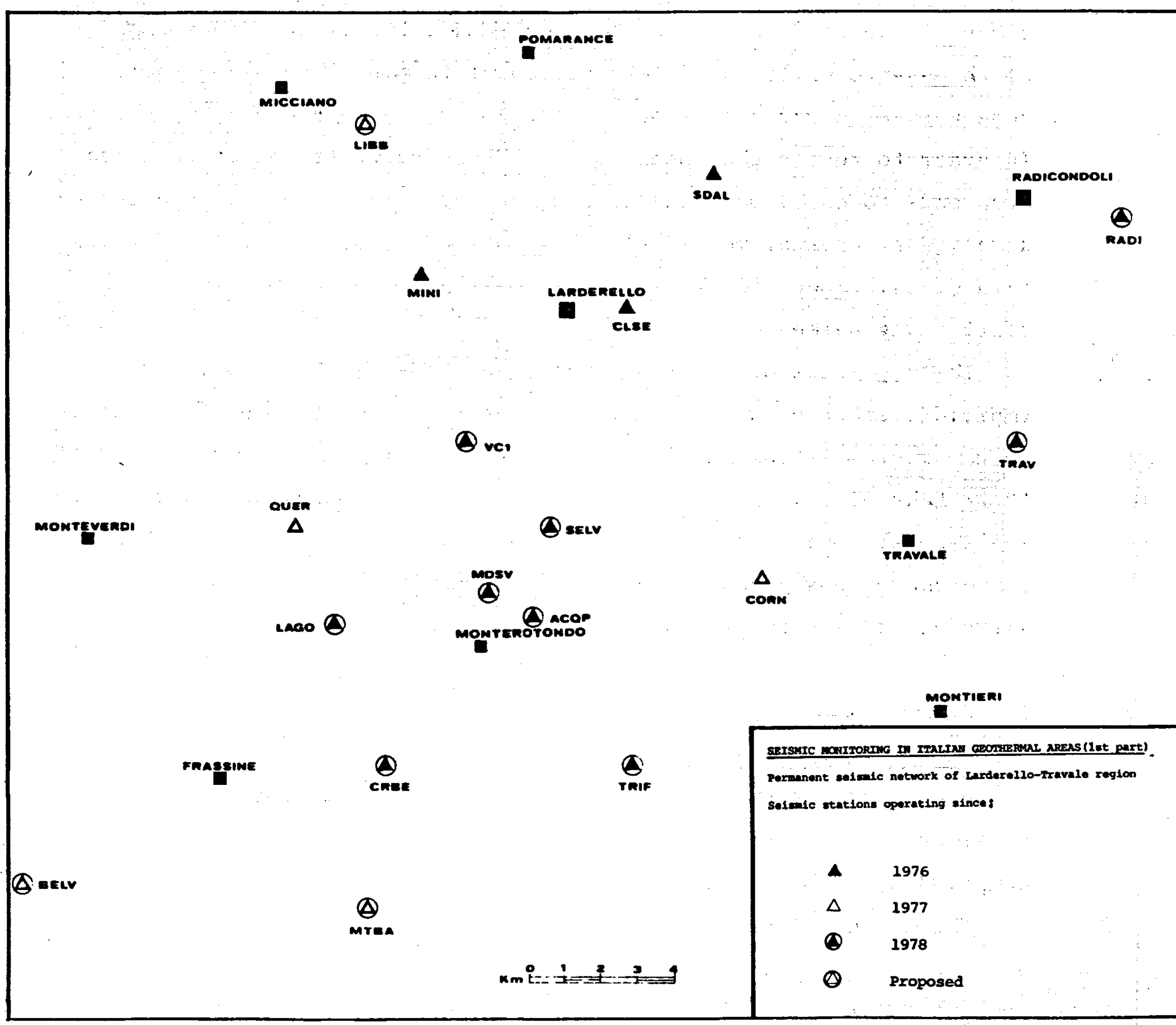


Fig. 2. Permanent seismic network of Larderello-Travale region.

station to another and is reconstructed on the basis of geologic (stratigraphy of the wells) as well as geophysical (seismic refraction and reflection, sonic logs) knowledge (Table 1). The mean square error of the residual travel time is less than 0.1 sec. for over 80% of the events while the determination of the focal co-ordinates is done with an error ⩾ 1 km on the horizontal plane and ⩾ 2 km at depth. In order to render the focal location more accurate, an attempt has been made to use a more advanced computing program, based on a three-dimensional crustal model (Alessandrini - Levato, 1980). The definition of this model for the Larderello-Travale geothermal region is still being worked on.

The magnitude of local seismic events is determined using an empirical equation which ties it to the total duration of the event, to the distance from the epicenter, and to the focal depth (Lee et al. 1972; Lahr et al. 1973). For events of greater magnitude, a comparison has been made between values determined with the method described above and values given by the National Seismic Network, and satisfactory agreement has been found.

5. SEISMIC ACTIVITY

5.1 Historical Seismic Activity

Historical seismic activity has been studied taking into consideration the data contained in the National Seismic Catalogue, compiled by ENEL, for the period 1000 - 1975.

The Larderello-Travale geothermal region is located on the western border of an area with an almost uniform seismic activity which extends towards the center of the Italian peninsula in a NW-SE direction (Fig. 3). The entire (strip) belt between the Tirrenean Sea and the Appennines which runs along the line of Livorno, Massa Marittima, up to Monte Amiata, is an almost aseismic area or one with very moderate seismic activity. In the immediate vicinity of the geothermal area shown in the small square, even though earthquakes of high intensity IX° - X° (prior to 1800) on the Mercalli scale have occurred, seismic activity has remained moderate and in the last few years seems to have decreased.

Table 1 - Crustal Model

STATIONS : MINI - CLSE		STATIONS : SDAL - TRAV - RADI	
Velocity km/sec	Depth. km	Velocity km/sec	Depth. km
3.800	0.	3.000	0.
5.100	0.150	5.100	0.440
6.200	3.900	6.200	4.200

STATIONS : QUER		STATIONS : CRBE	
Velocity km/sec	Depth. km	Velocity km/sec	Depth. km
2.800	0.	3.800	0.
3.800	0.040	5.500	0.100
5.100	0.240	5.100	0.800
6.200	3.500	6.200	3.500

STATIONS : VC/1		STATIONS : MDSV	
Velocity km/sec	Depth. km	Velocity km/sec	Depth. km
3.800	0.	4.200	0.
4.200	0.200	5.500	0.010
5.500	0.800	5.100	0.800
5.100	1.100	6.200	3.000
6.200	3.500		

Table 1. Crustal Mode (Continued)

STATIONS : CORN - TRIF		STATIONS : LAGO	
Velocity km/sec	Depth. km	Velocity km/sec	Depth. km
5.100	0.	3.200	0.
5.500	0.010	5.100	0.300
6.200	4.200	6.200	3.500

STATIONS : SELV		STATIONS : ACQP	
Velocity km/sec	Depth. km	Velocity km/sec	Depth. km
3.800	0.	4.200	0.
4.300	0.100	5.100	0.010
5.100	0.700	6.200	3.100
6.200	3.400		

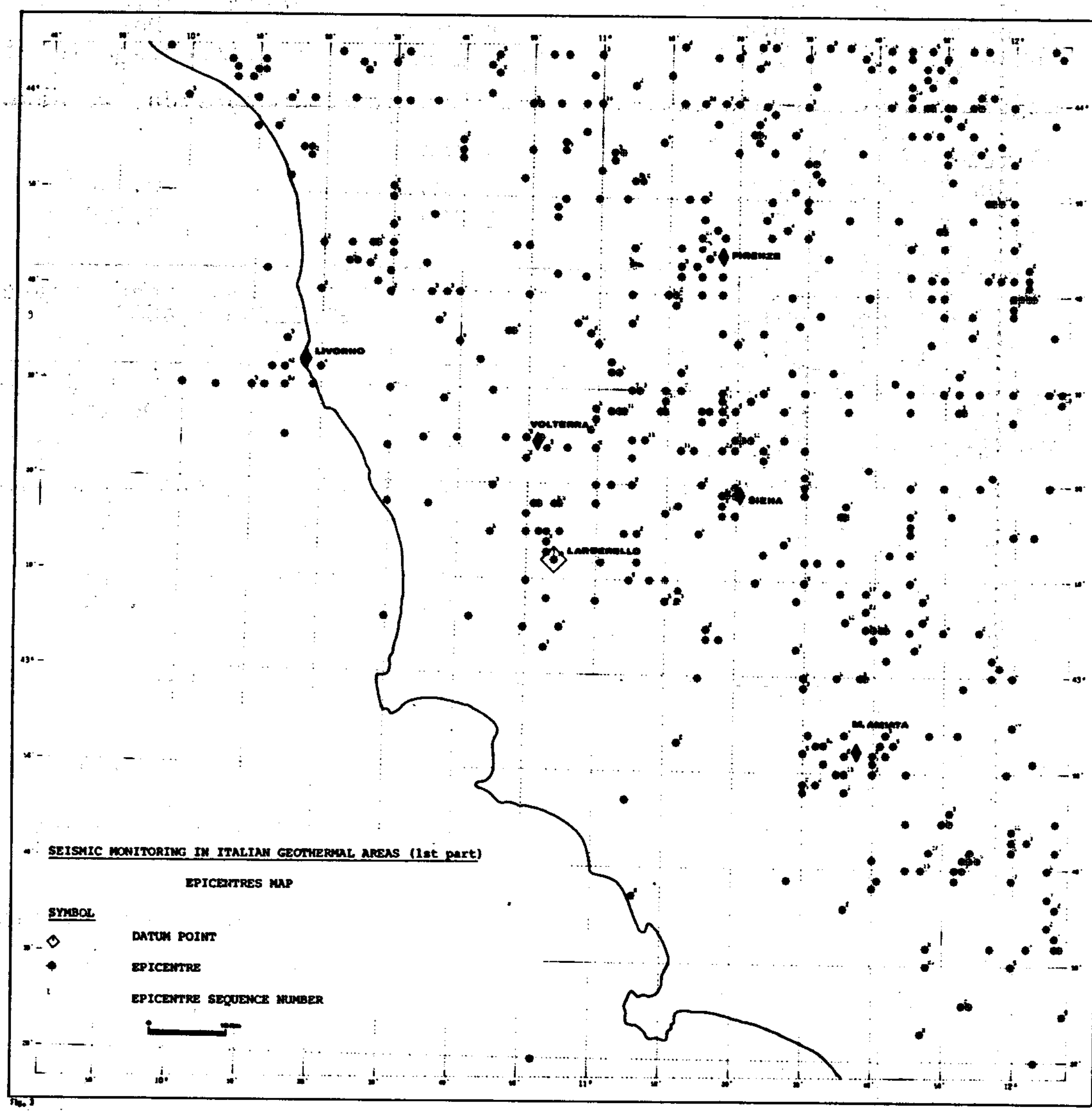


Fig. 3. Epicenters map.

The only noteworthy event verified in recent times is the earthquake at Monterotondo on August 19, 1970 with an intensity of VII° on the Mercalli scale. Since the catalogue appears to be complete from 1880 to 1975 even for earthquakes of low magnitude ($M > 3$), an area which includes the Larderello-Travale geothermal region has been chosen (Fig. 4) in which to attempt to make a statistical table of magnitudes; using the empirical equation of Ishimoto-Iida, we have obtained a value of "b" equal to about 1.5.

5.2 Present Seismic Activity

From March 1977 to July 1980 about 500 events have been located, almost 400 of which fall within the geothermal region. Seismic activity manifests itself by sporadic activity and sequences of events which appear in clusters vary in magnitude and number. These rarely take on the form of typical mainshock aftershock sequences and consist of earthquakes which follow one another in a time range which varies from a few seconds to several hours, with an epicenter which is restricted to a small area.

The maximum magnitude observed during the above mentioned period was 3.8. From the distribution of epicenters (Fig. 5) it may be concluded that seismic activity is present throughout the entire Larderello-Travale geothermal region, but in certain areas there is a greater concentration.

These areas are located at the borders of the geothermal region and coincide with areas whose exploitation has begun in recent times. At any rate, it is noteworthy that only in the Lago area (SW of Larderello) does the release of tension come about in a regular, continuous manner. During the period of observation here considered, it was possible to single out isolated spots of seismicity even in areas not seismically active (i.e., the immediate vicinity of well "Sasso 22" drilled during the period 1978-1979 to a depth of more than 4/km). The projection of the foci on vertical planes running N-S and E-W (Figs. 6-7) demonstrates that earthquakes take place almost totally within 8 km and predominantly at 3-4 km.

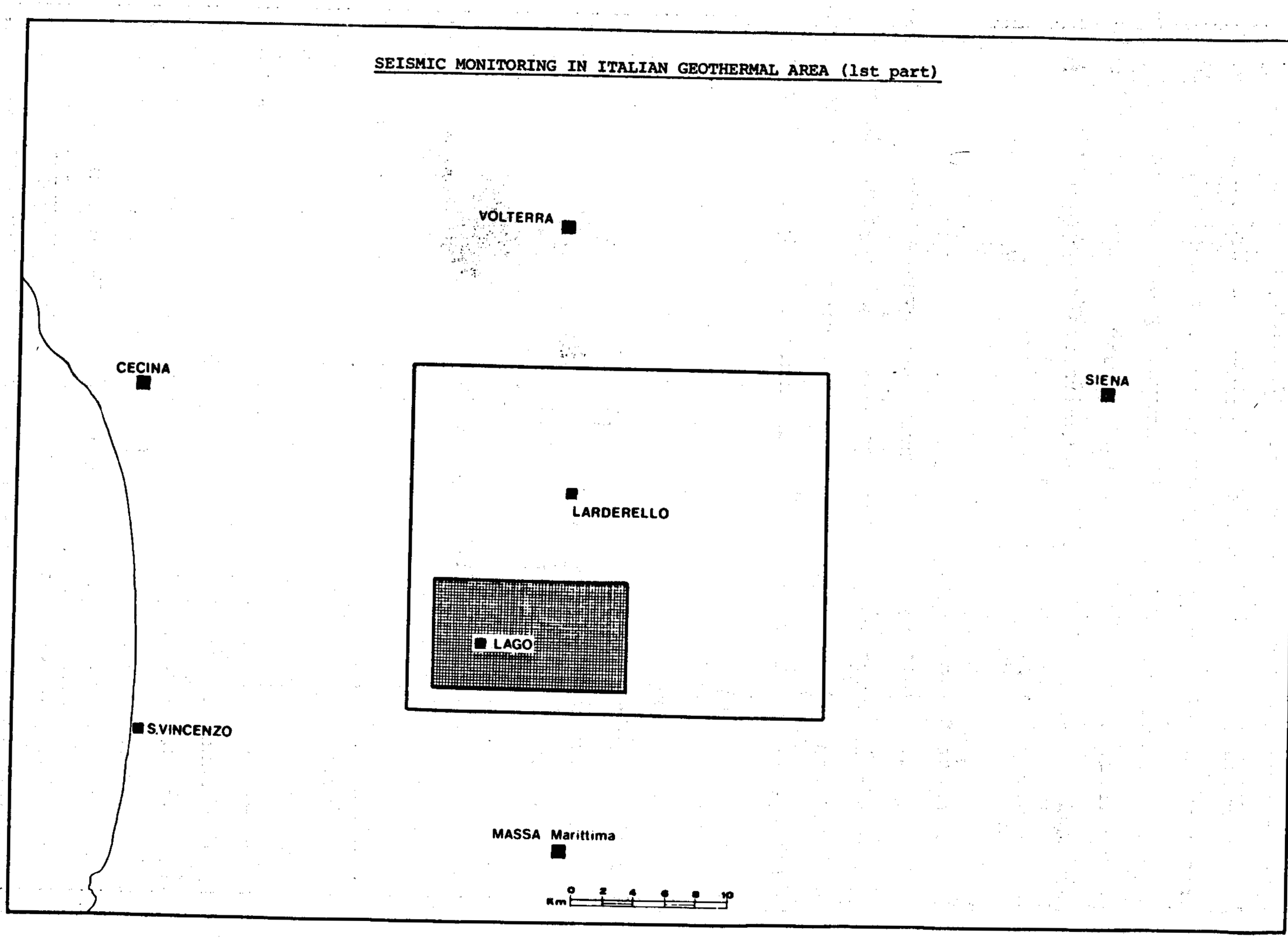


Fig. 4. Index map of historical and actual seismicity.

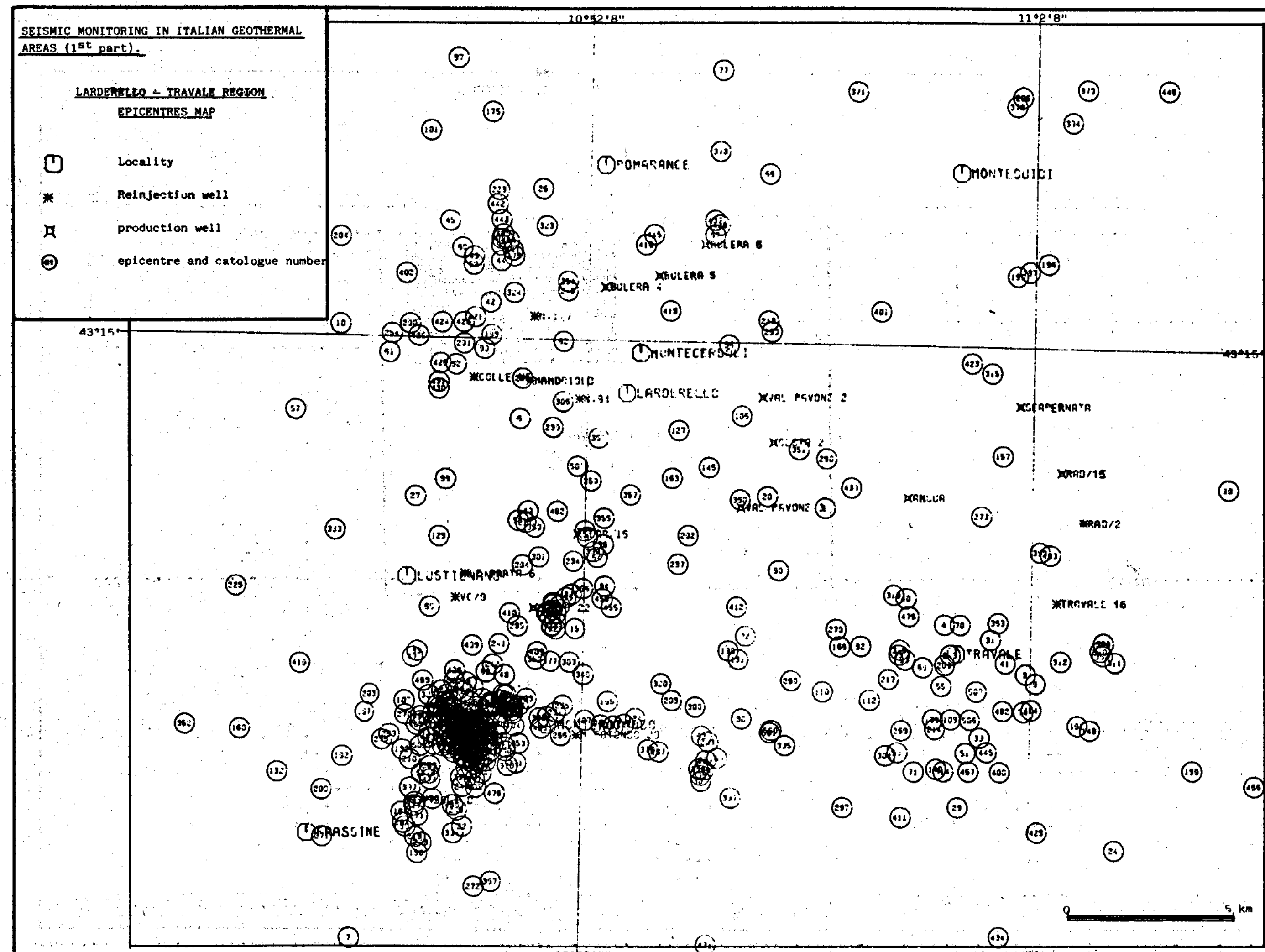


Fig. 5. Larderello-Travale region epicenters map.

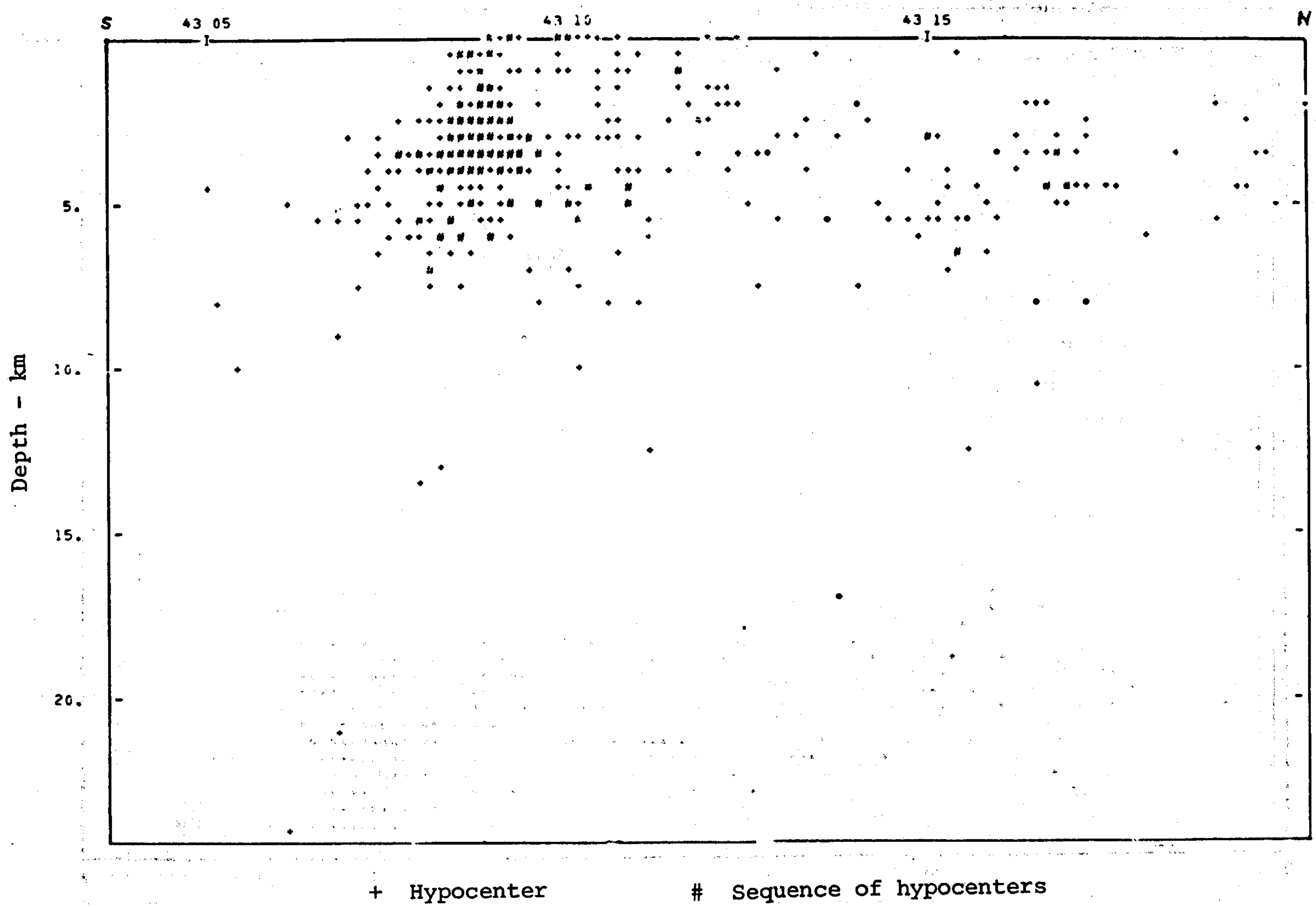
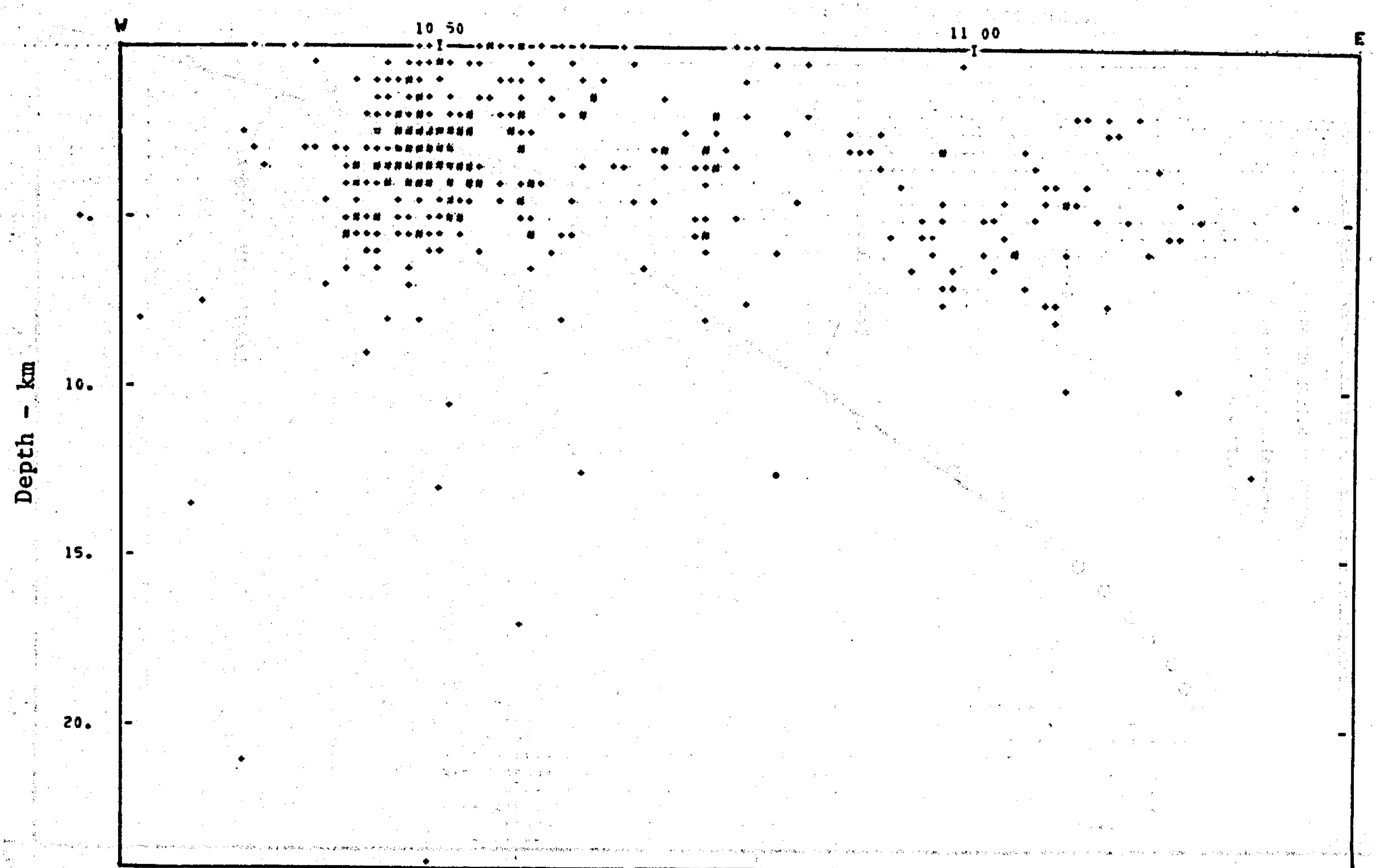


Fig. 6. Hypocenters distribution on N - S section.



\+ Hypocenter # Sequence of hypocenters

Fig. 6A. Hypocenters distribution on E - W section.

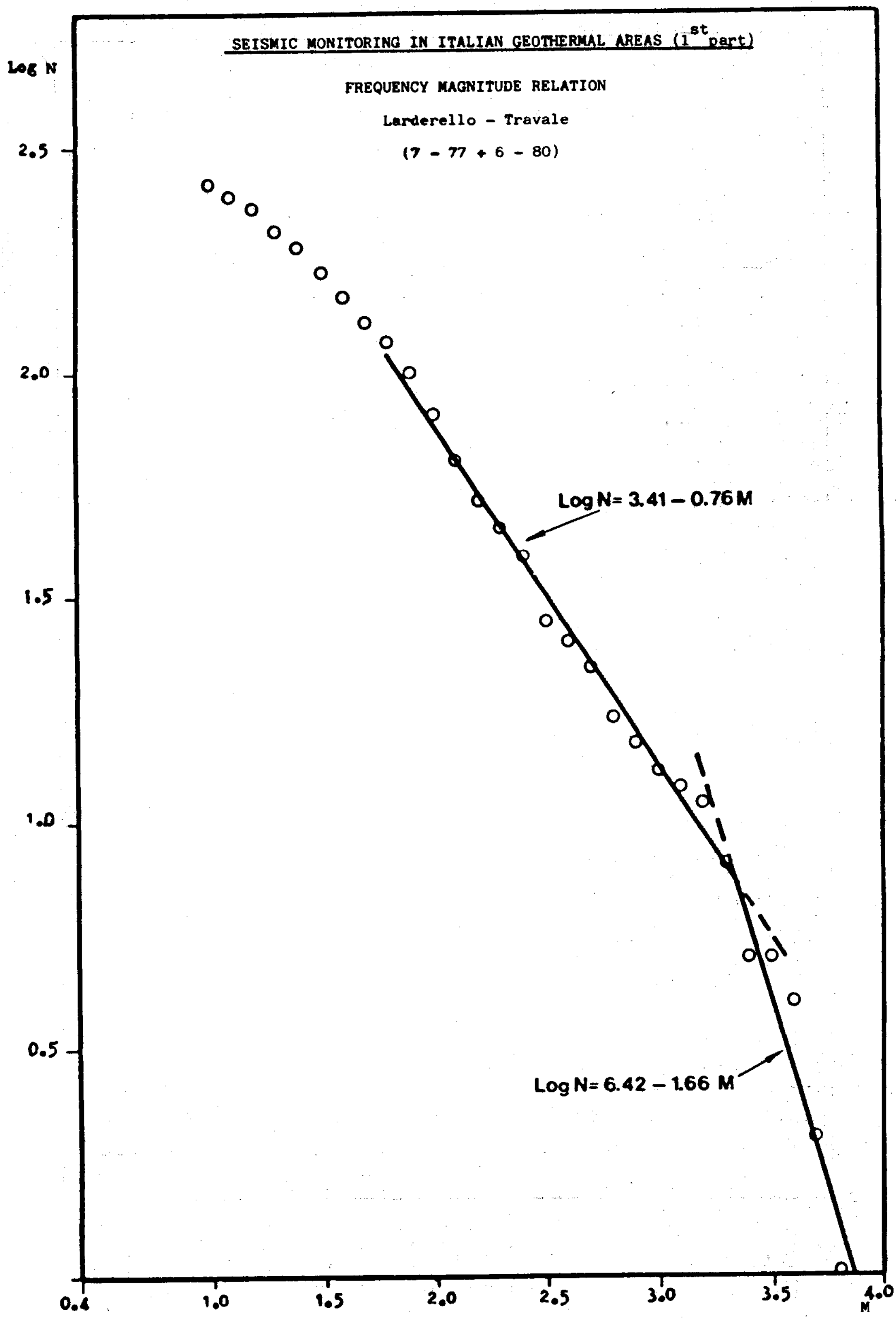


Fig. 7. Frequency magnitude relation Larderello-Travale areas.

It is interesting to note the abrupt interruption in seismicity in correspondence to the W limits of the Larderello geothermal field (Figs. 6-6a) and a progressive deepening of the foci in the eastern zone corresponding to the geothermal field of Travale.

The scarce seismicity observed in the central part of the region may coincide with a less fractured zone which may constitute an eventual barrier between the two geothermal fields.

5.3 Magnitude - Frequency Relationship

The magnitude-frequency histogram has been drawn up for the events localized in the area indicated in the square in Fig. 3 over a three-year period extending from July 1977 to July 1980. The histogram (Fig. 7) presents three distinct slopes: the first for $M > 1.8$ may be attributed at least partly to instrumental detection factors; there is then a stretch which goes from $1.8 > M > 3.3$ which may be approximated by the straight line whose equation is:

$$\text{Log } N = 3.42 - 0.76\, M$$

Finally, for $M > 3.3$ we see an abrupt increase in the slope which corresponds to a "b-value" of about 1.66. Similar lack of linearity has been found in studies done on microseismicity (6 Scalera, 1980, Analysis of the "b" parameter; Seeberg, personal communication). The same type of histogram (Fig. 8) has been constructed from the events which took place during the same period of observation in a more restricted area indicated in Fig. 3, Lago (SW of Larderello).

In this case the stretch which runs from 1.8 — 3.3 may be approximated by the straight line with the following equation:

$$\text{Log } N = 3.97 - 1.19\, M$$

The value of b (1.19) which we find in this last case is notably greater than that relative to the entire region studied.

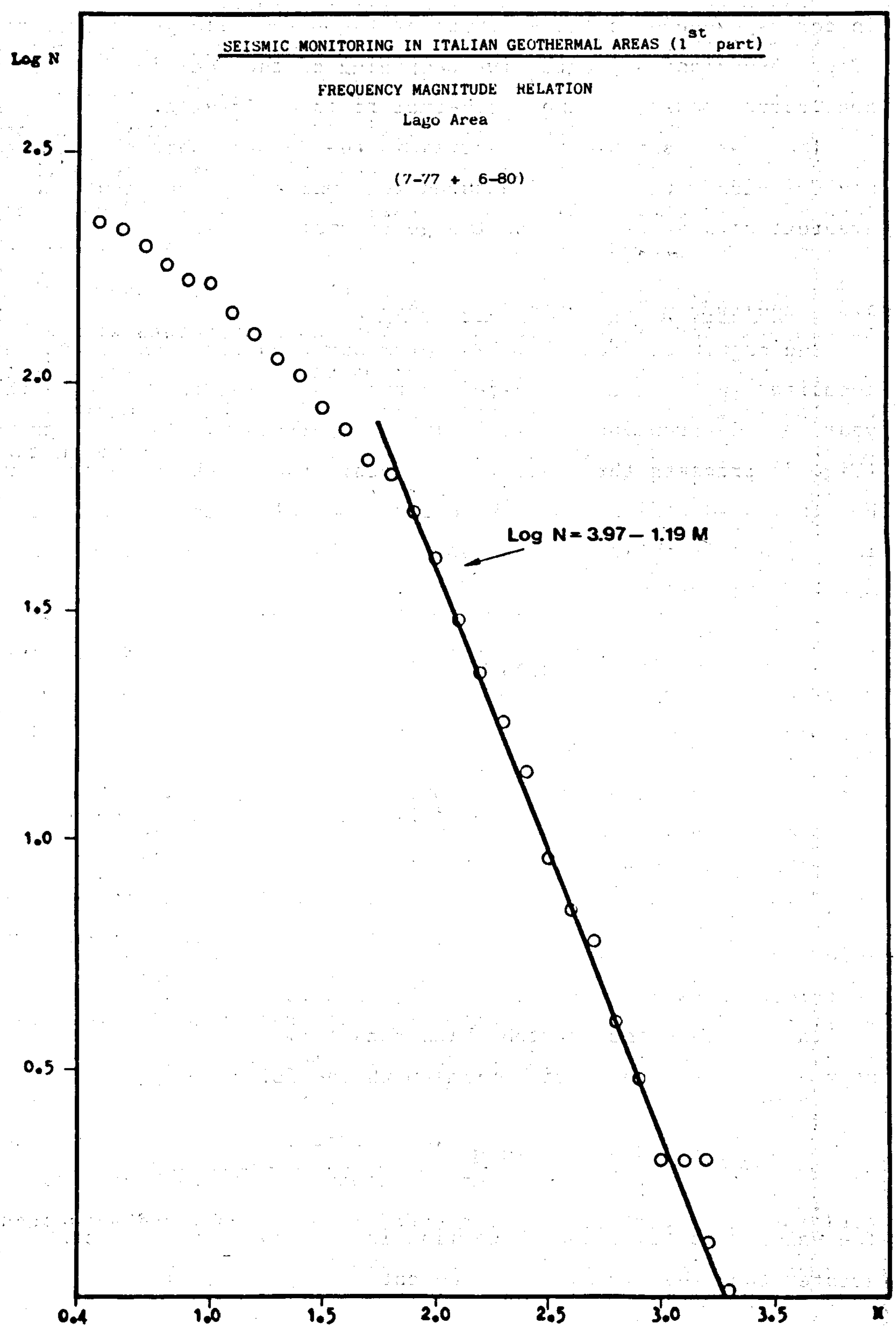


Fig. 8. Frequency magnitude relation Lago area.

This may be connected to a geological situation which is particularly favorable to the release of energy with mechanisms characterized by low tension. This value of "b", characteristic also of other geothermal areas (Marks et al. 1978), is generally associated with a high grade of fracturing of rocks and in some cases with induced seismic activity (Gupta - Rastogi, 1976). A "b" value equal to about 1.5, drawn from data in the National Catalogue of earthquakes which took place from 1880 to the present in the area shown in Fig. 3, is comparable to that calculated on the basis of events with $M > 3.3$ which took place during the observation period (1977 - 1980) in the area shown in the larger square; this confirms the seismically abnormal behaviour with respect to the average value found in the national territory ($b \simeq 0.9$) (Jaccarino, 1968).

6. FOCAL MECHANISMS

The focal mechanism has been determined employing the classical method based on an analysis of the first motion recorded. A computing program has been utilized (Wickens, Hodgson, 1967), adapted to the present problem, which determines the best orientation of nodal planes with relation to the input data.

Given the low energy released by the single seismic events verified in the area studied during the past three years, it has been impossible to utilize, in order to determine focal mechanisms, data from stations which do not belong to the local network at Larderello. The scarce number of available stations and their location with respect to the events has limited the reliability of the results obtainable with an analysis of the first motions of every single earthquake.

In order to obtain more stable solutions of fault planes, the joint fault (or composit) plane solutions method has been used, applying it to earthquakes originated in a well-defined seismogenetic area or even belonging to the same sequence.

The results shown in Fig. 9 are the most representative for the whole region according to the present seismographic coverage. In particular the following features are evidenced:

- frequent mechanisms of normal faults with appennine direction (NW-SE) and antiappennine (NE-SW).

- strike-slips fault mechanisms with the axis of maximum compression trending approximately NW-SE.

7. SEISMICITY - EXPLOITATION OF GEOTHERMAL FIELDS

A comparison between seismicity and activity connected to exploitation of a geothermal field (extraction and injection of fluids at depth, drilling of deep wells in total loss of circulation, stimulation of sterile wells, etc.) has been attempted in order to establish if and how these activities modify the stress release mechanisms of the Larderello-Travale region. The data concerning the quantity of fluids extracted and injected in the subsoil has been compared with the seismic energy which is released every month.

From the histograms reconstructed for the Larderello-Travale geothermal region (Fig. 10) the seismic energy was released as a linear function of time until May 1979, when a sharp increase of seismicity occurred. This increase can not be correlated to either the quantity of fluids injected or to production of fluid or to the average monthly rainfall.

Observing the variations of the same parameter for the Lago area (Fig. 11), we can see that the same pattern in the energy histogram persists throughout the period from May 1979 - June 1980. In this case there are no sure correlations between extraction of injection activities and seismicity. At any rate it is noteworthy that, during the period of March 1978 - January 1980, a deep well was drilled (Sasso 22) in the Lago area; the drilling was performed largely in total loss of circulation injecting large quantities of water into the well. The number of seismic events with a magnitude superior to 1.5

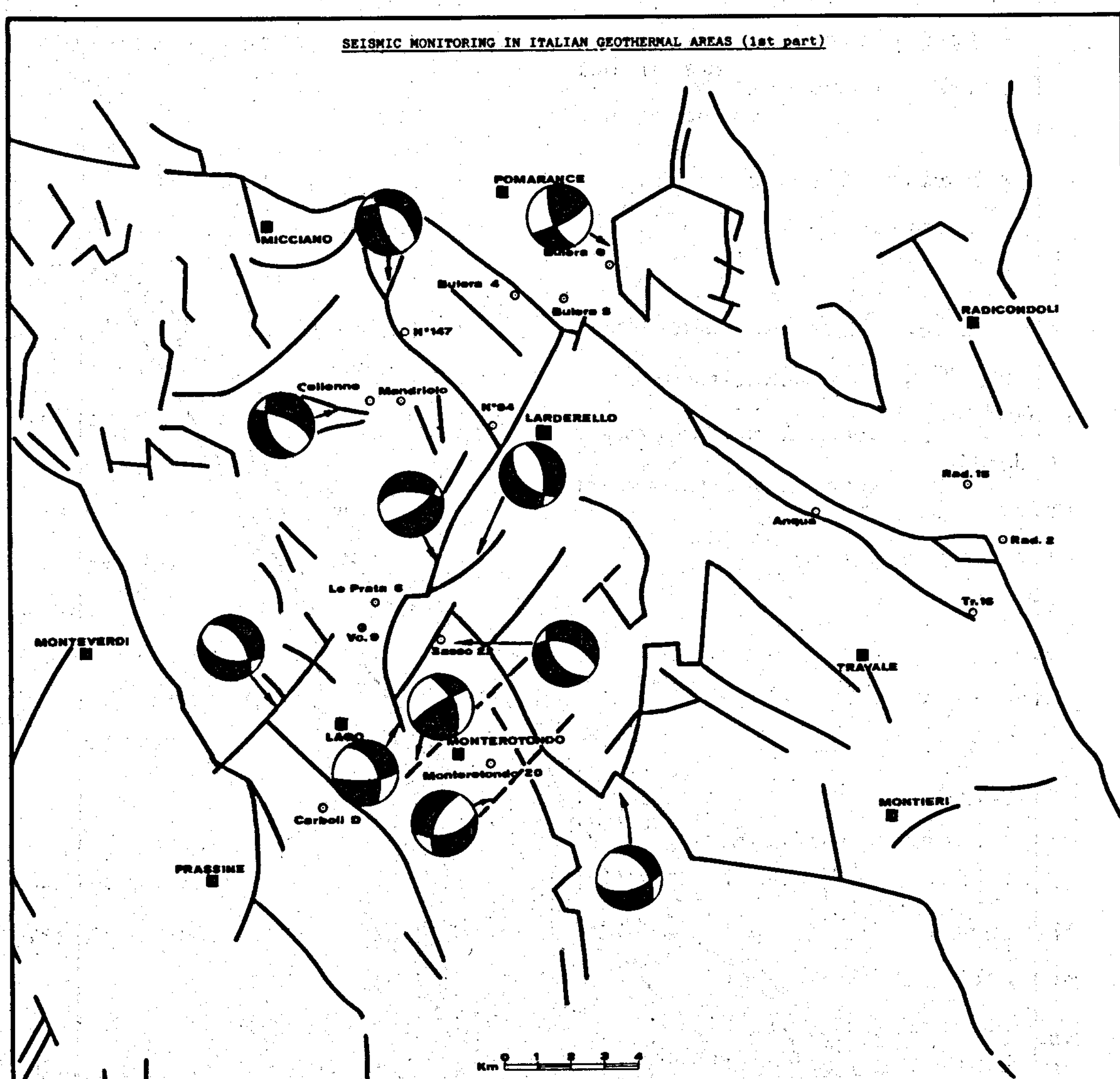


Fig. 9. Representative fault plane solution and main tectonic trends in Larderello-Travale region.

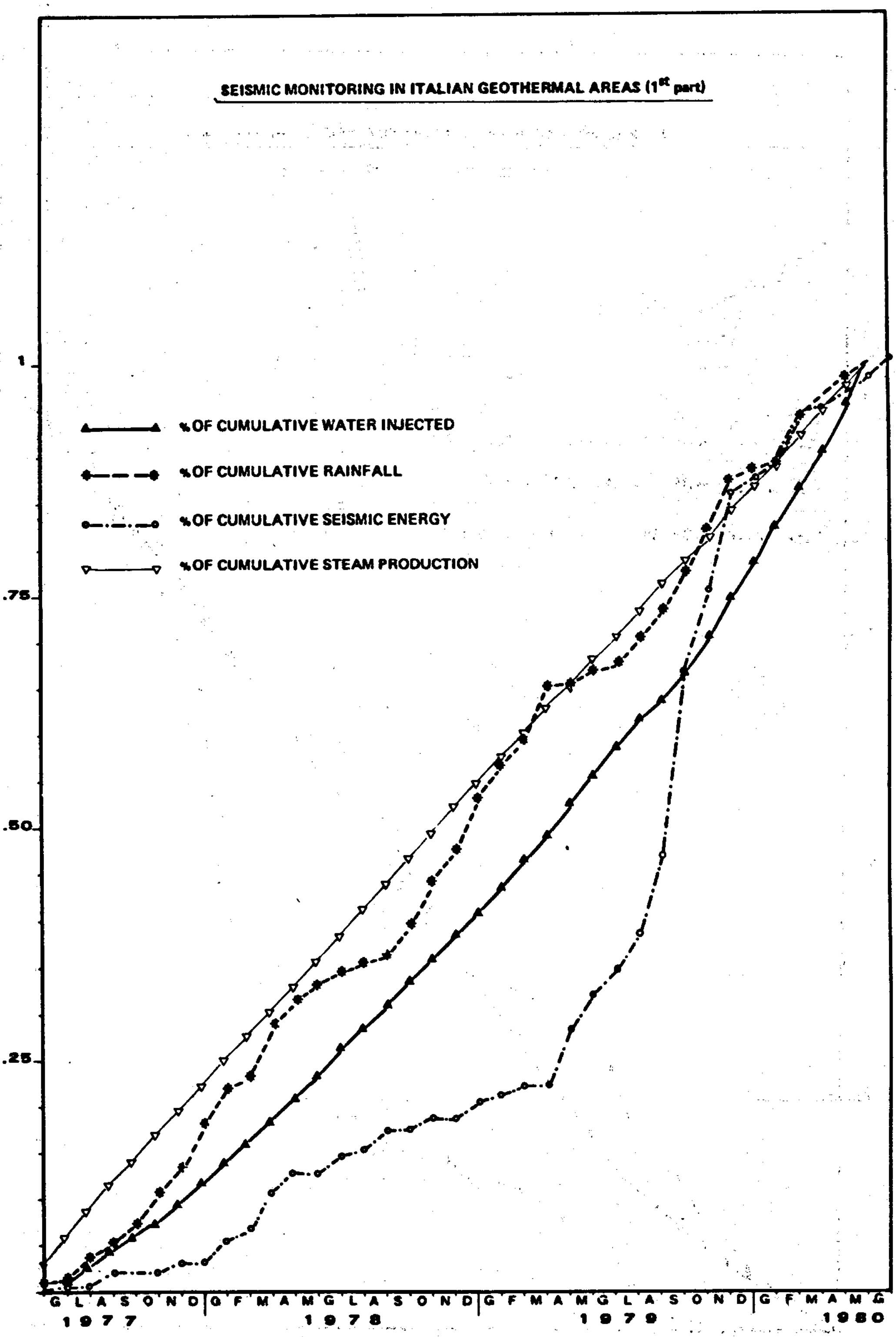


Fig. 10. Temporal distribution of seismic energy released, water injected, rainfall, steam production.

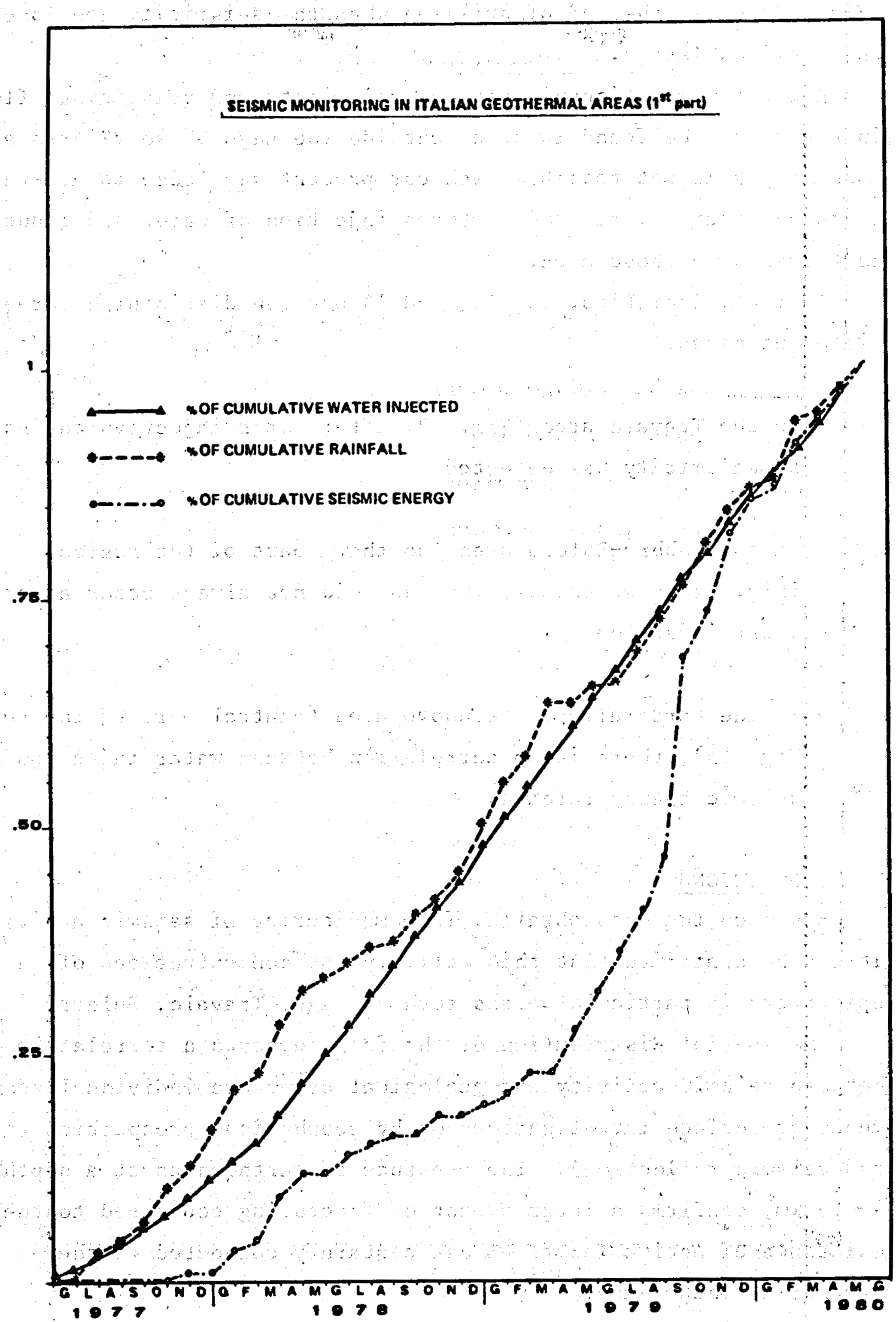


Fig. 11. Temporal distribution of seismic energy released, water injected, rainfall.

increases gradually as the depth of the well reaches about 3000 m (Fig. 12) until the end of drilling when the seismicity goes back to the previous levels.

A certain relationship between seismicity and quantity of fluid injection may be found in areas outside the Lago-Sasso 22 area also. However, it is not possible with our present knowledge to generalize a cause-effect relationship between injection of water and induced earthquakes in those area.

In fact, from Figs. 13, 14, and 15 one can distinguish three different cases:

- in the Travale area (Fig. 13) after water injection an increase of seismicity was detected.

- in the Gabbro-Bulera area (northern part of the region) (Fig. 14) a seismicity increase did not always occur after water injection.

- in the Larderello-Castelnuovo area (central part of the region, Fig. 15), there is no correlation between water injection and seismic energy release.

8. CONCLUSIONS

Based on the data obtained from monitoring of seismic activity, it can be confirmed that this activity has concentrations of epicenters in particular areas such as Lago, Travale, Bulera.

The spatial distribution of the foci suggests a correlation between seismic activity and geological structure individualized by means of surface investigations or by geophysical prospecting (gravity and seismic reflection). The presence of earthquakes at a depth of 4 — 5 km, confirms a large amount of fracturing connected to the existence of active faults almost certainly connected to the geothermal phenomenon.

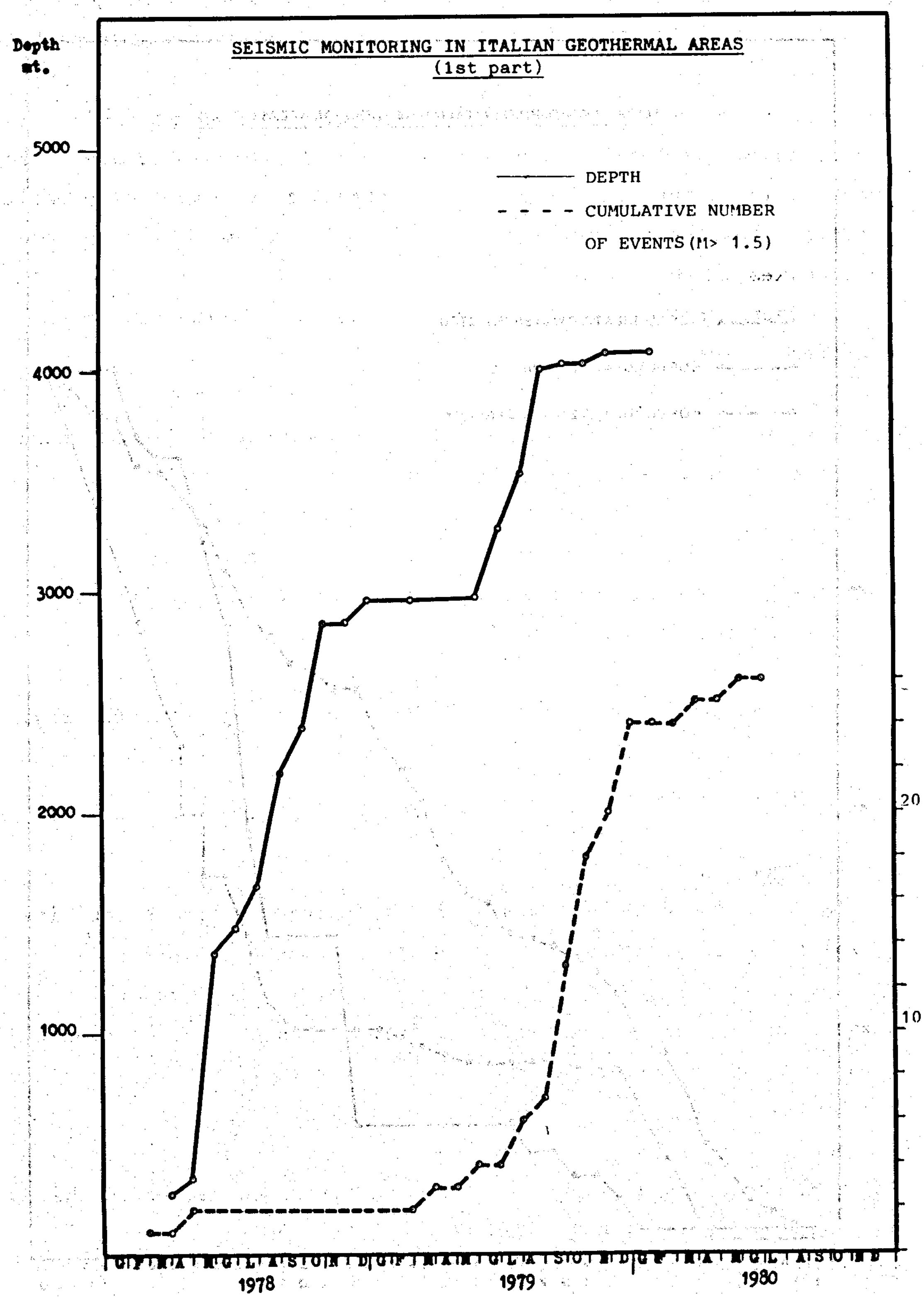


Fig. 12. Sasso 22 deep-well. Depth vs seismicity.

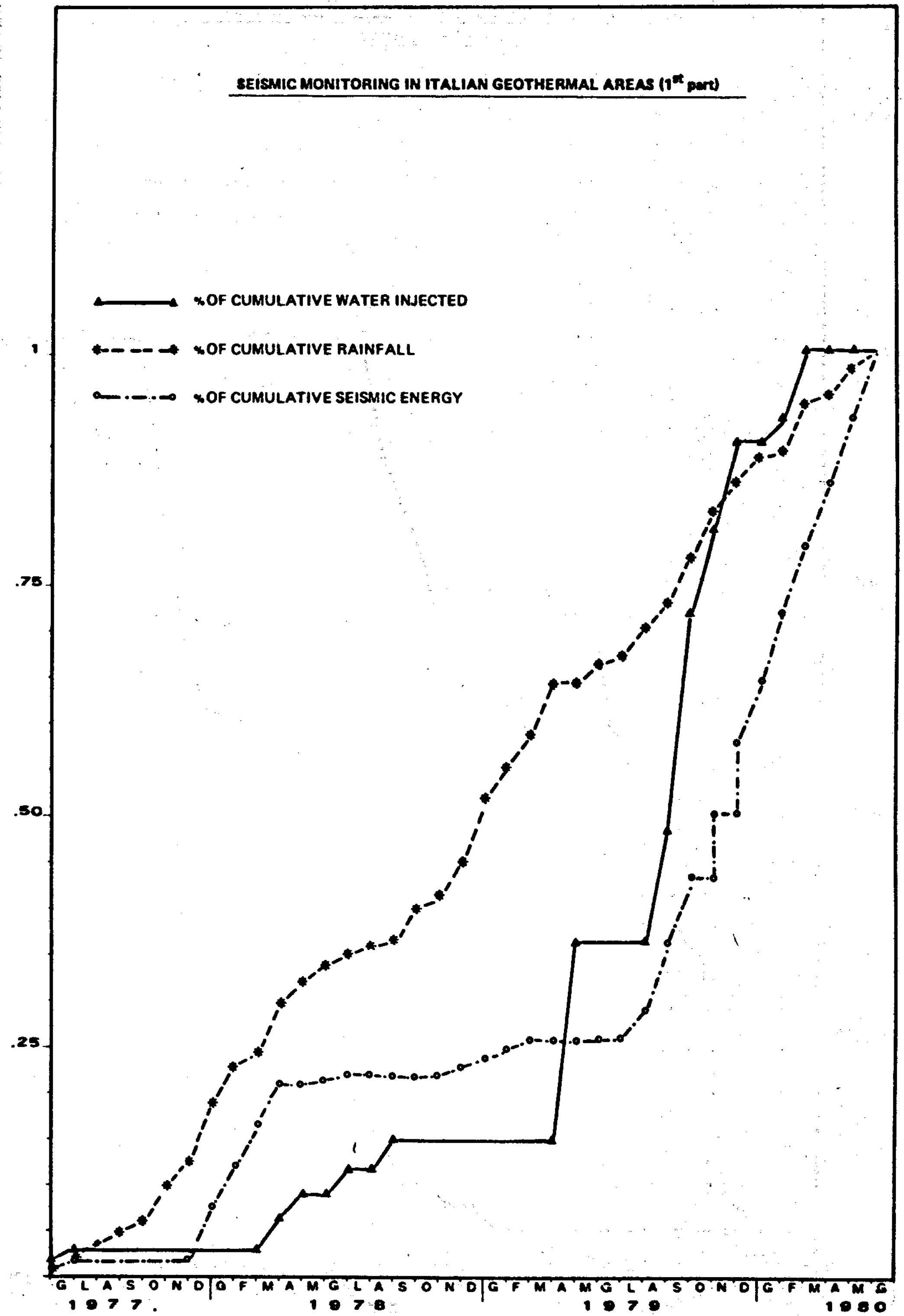


Fig. 13. Temporal distribution of seismic energy released, water injected, rainfall.

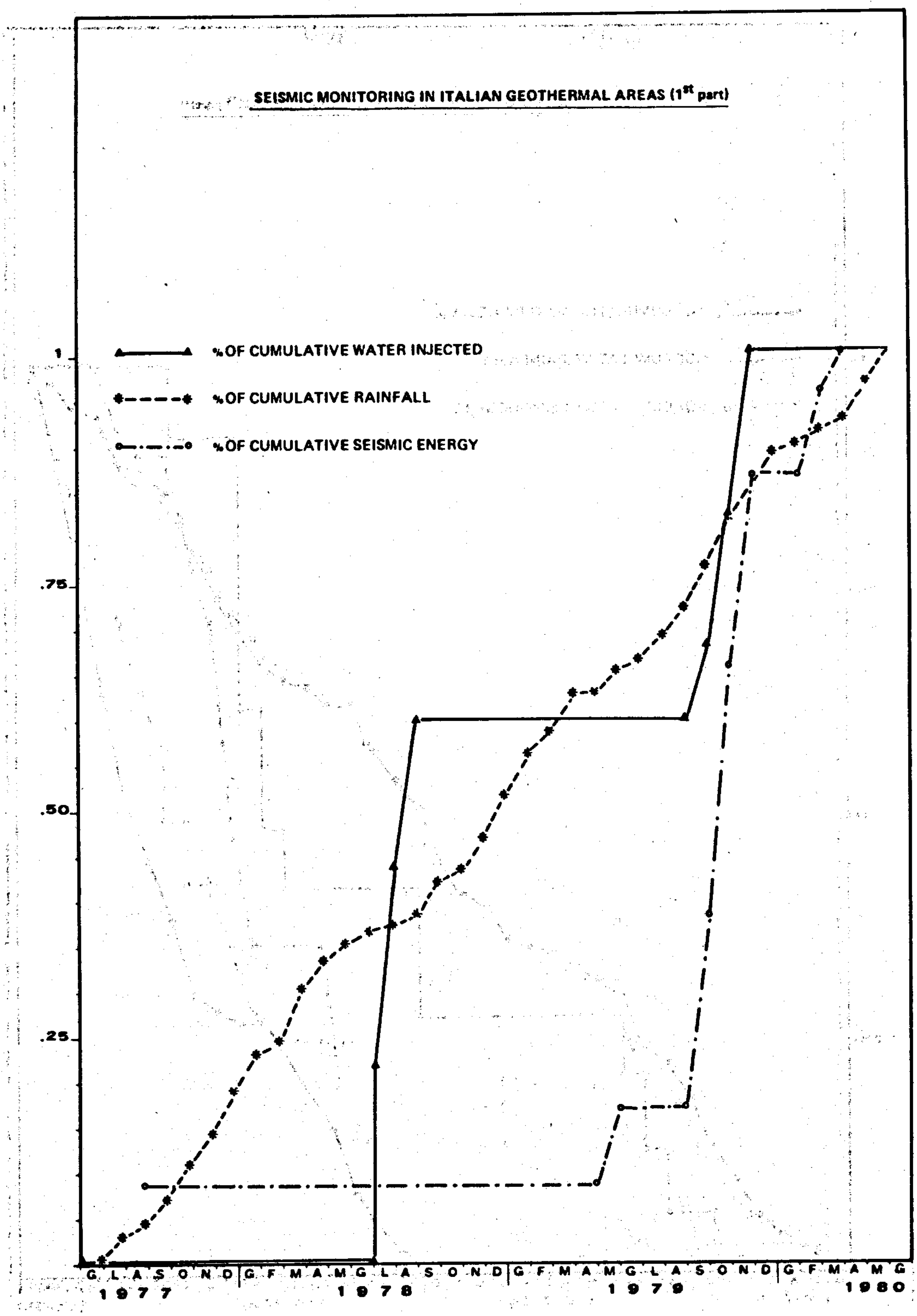


Fig. 14. Temporal distribution of seismic energy released, water injected, rainfall.

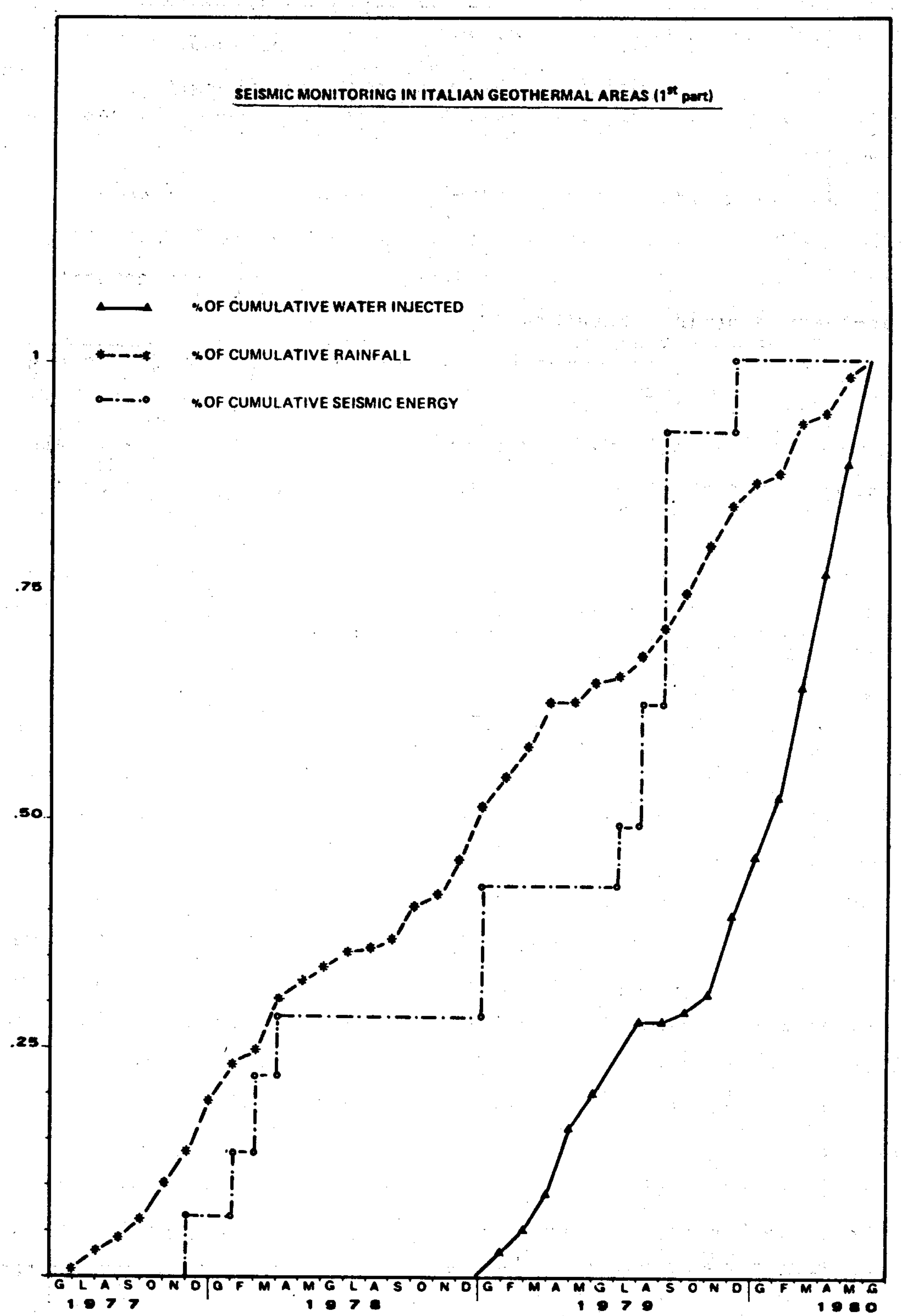


Fig. 15. Temporal distribution of seismic energy released, water injected, rainfall.

The study of focal mechanisms gives us some information on possible directions and inclinations of the faults which agree with the geological-structural data. It has been possible to recognize normal fault mechanisms with sub-vertical inclinations, and, to a lesser degree, strike-slip fault mechanisms from which we can see that the direction of maximum compression is the anti-appennine one (SE-NW).

Given the limited amount of time during which the seismic monitoring has been carried out, it is not yet possible to find a certain relationship of cause and effect between seismic activity and fluid-thermodynamic parameters.

As a matter of fact, even if some phenomena localized in space and time (Sasso 22, Bulera, Travale) allow us to see an influence of the injection of fluids in the subsoil on the seismicity, there is also evidence of no correlation in other parts of the region (Larderello-Travale). These facts lead us to make some hypotheses.

In the Larderello-Castelnuovo area the water, injected in a steam dominated reservoir rapidly passing into a gas phase, does not cause appreciable variations in the hydrodynamic equilibria.

On the contrary in water dominated reservoirs, as in Bulera-Gabbro, Travale, Sasso 22 areas, even small amounts of water injected can cause noticeable pore pressure variations. In particular tectonic conditions, such as variations diminishing the effective normal stress, modify the stress release conditions.

Naturally the results and considerations presented in this report are not definitive; more conclusive results may be obtained when we reach a greater accuracy in the determination of focal co-ordinates, subordinate to a more detailed knowledge of the crustal model. A more accurate determination of focal mechanisms will be possible employing a greater number of seismic stations when more information is available from spectral analysis. Lastly it will be necessary to have a period of observation long enough to get a better knowledge of temporal correlation between seismic activity and parameters connected to the activity of the field.

9. REFERENCES

See the following article for references cited here.