SEISMIC MONITORING IN ITALIAN GEOTHERMAL AREAS
II. SEISMIC ACTIVITY IN THE GEOTHERMAL FIELDS DURING EXPLORATION

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1. INTRODUCTION

The Italian areas of geothermal interest are usually located in densely populated zones and very often near centres of historical and artistic renown. Consequently, monitoring of seismic activity induced by exploration and exploitation of these geothermal resources becomes of particular importance, demanding a considerable effort on ENEL's part (Index Map).

Work began a few years ago on setting up a microseismic control network in each of the localities involved in deep exploration for geothermal purposes. Wherever possible the network was installed before drilling began in order to obtain a preliminary picture of the natural background noise.

As the control system had to be put into operation as quickly as possible and create a minimum of operational problems, it was decided to begin with an analogic instrumentation, which is economic, autonomous, and easy to install. The instrumentation, described in the first part of our report, provided a continuous, comprehensive monitoring of all the local and regional seismic activity.

This report will present and discuss the data recorded from the beginning of the survey to June 1980. The data refer to natural seismic activity as well as to events recorded during production and injection tests in some wells.

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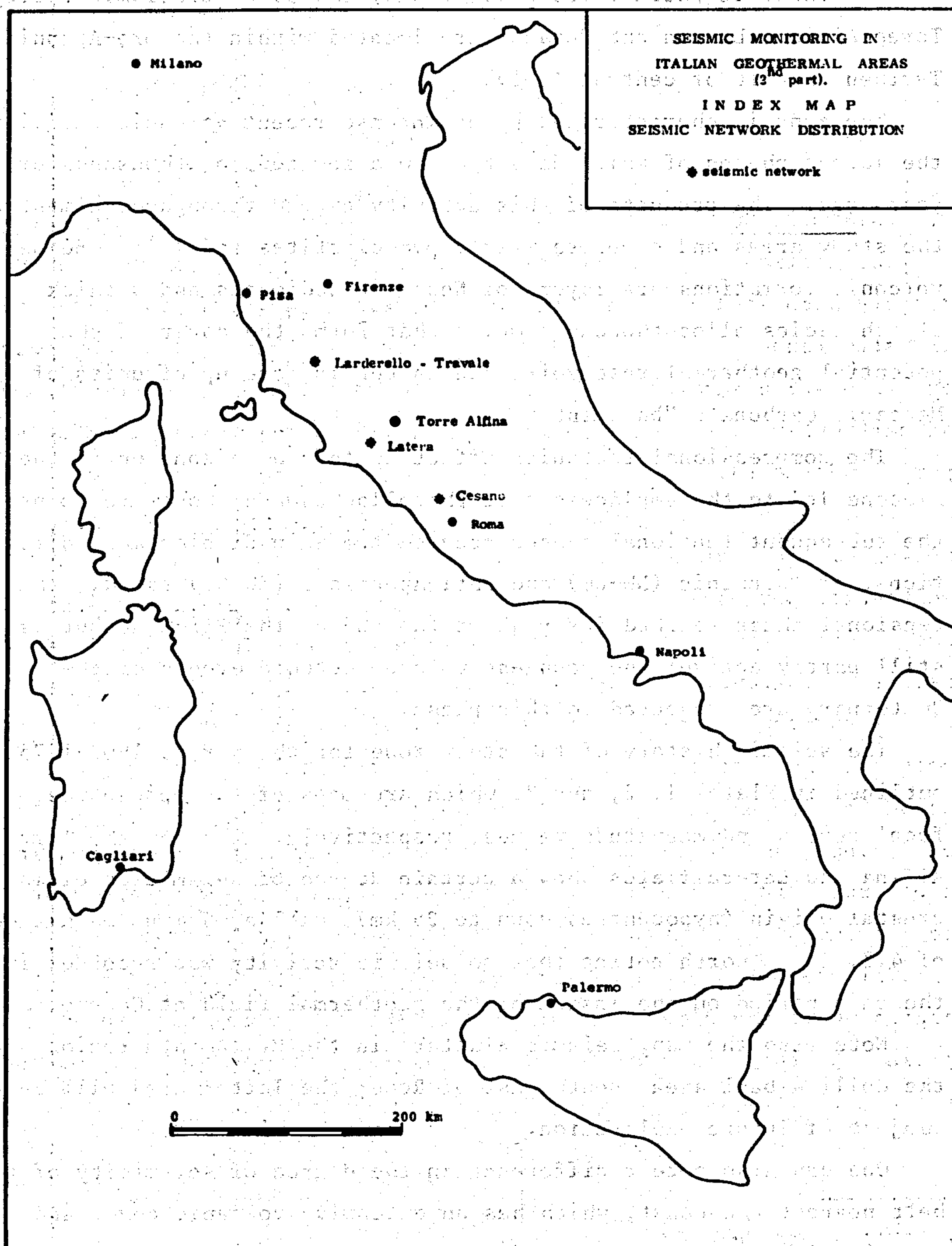

Index Map - Seismic Network Distribution

2. GEOLOGICAL BACKGROUND AND PAST SEISMIC ACTIVITY

The three geothermal areas covered by the passive seismic surveys, Toree Alfina, Latera and Cesano, are located within the pre-Apenninic Tyrrhenian belt of central Italy.

The zone is characterized by an intense recent volcanic activity, the latest phases of which date back to a few tens of thousands of years ago. The products of this activity extend throughout almost all the study areas and comprise mainly pyroclastites and lava. Below the volcanic formations are layers of Neogenic sediments and a thick flysch facies allochthonous complex that forms the cover of the potential geothermal reservoir; the latter is made up of units of Mesozoic carbonate "basement."

The compressional tectonics affecting the whole zone until the Mid Miocene led to the emplacement of the allochthonous cover terrains; the subsequent tensional phases created two main displacement directions, of Apenninic (NW-SE) and anti-Apenninic (SW-NE) trend. The tensional phase reached its peak at the end of the Pliocene but is still partly active; the youngest volcanotectonic events of the Quaternary are connected to this phase.

The seismic history of the study zone for the period 1900-1975 is outlined in Plates 1, 2, and 3, which are maps of the epicentres, focal depths and magnitude values, respectively. Whereas the Torre Alfina and Latera fields show a certain degree of seismicity of mainly crustal origin (hypocentres down to 25 km), with a maximum magnitude of 4.7, it is worth noting that no seismic activity was recorded in the said period on the inside of the geothermal field at Cesano.

Note also the many seismic clusters in the Mt. Amiata region and the Colli Albani area, south-east of Rome; the latter area will be the subject of future exploration.

One can also note a difference in the degree of seismicity of the belt nearest the coast, which has an extensive volcanic cover and seismic clusters concentrated in certain well-defined areas, and that of the Apennine ridge, whose seismic centres have a greater density and are more widely spread.

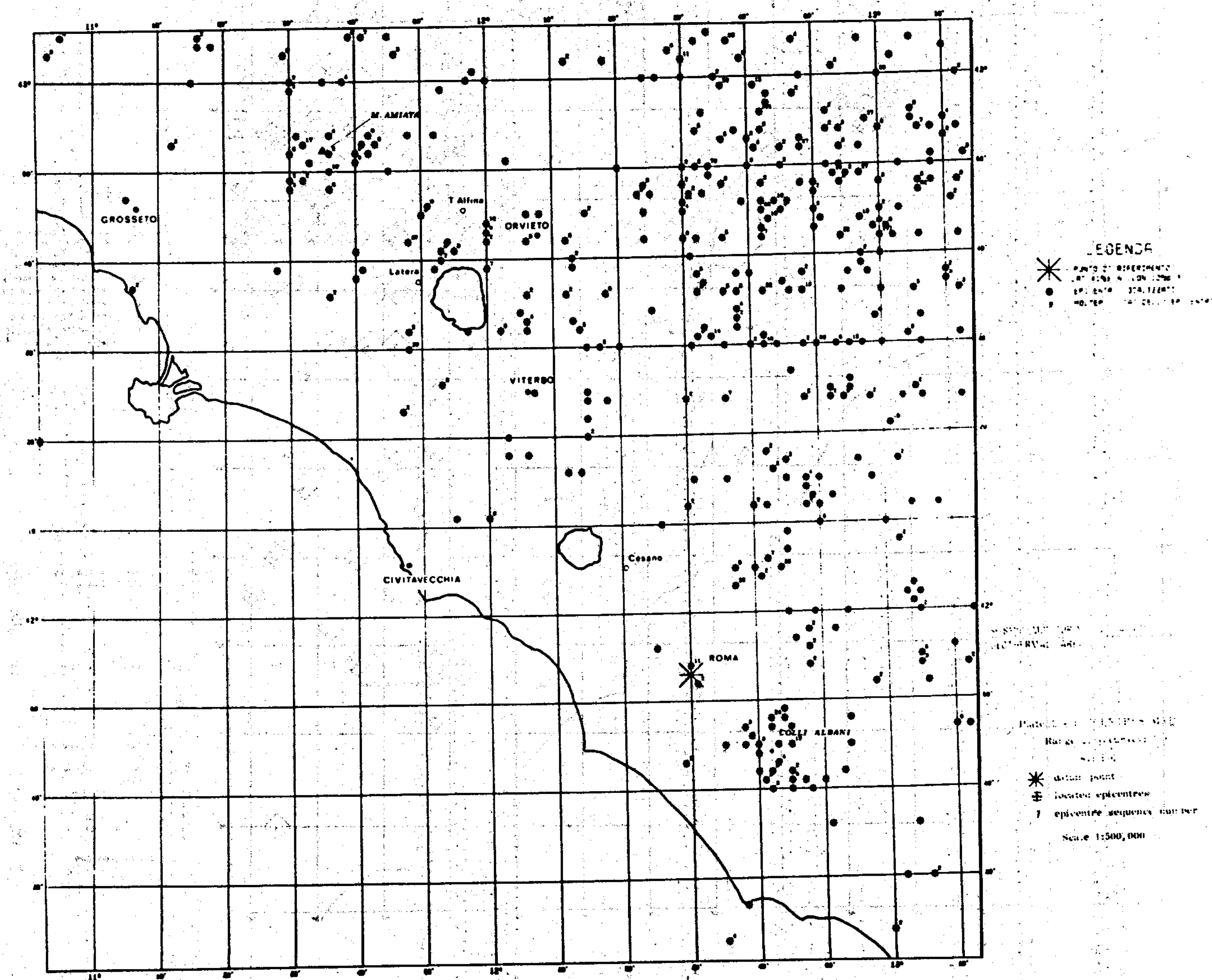

Plate 1. Epicentres.

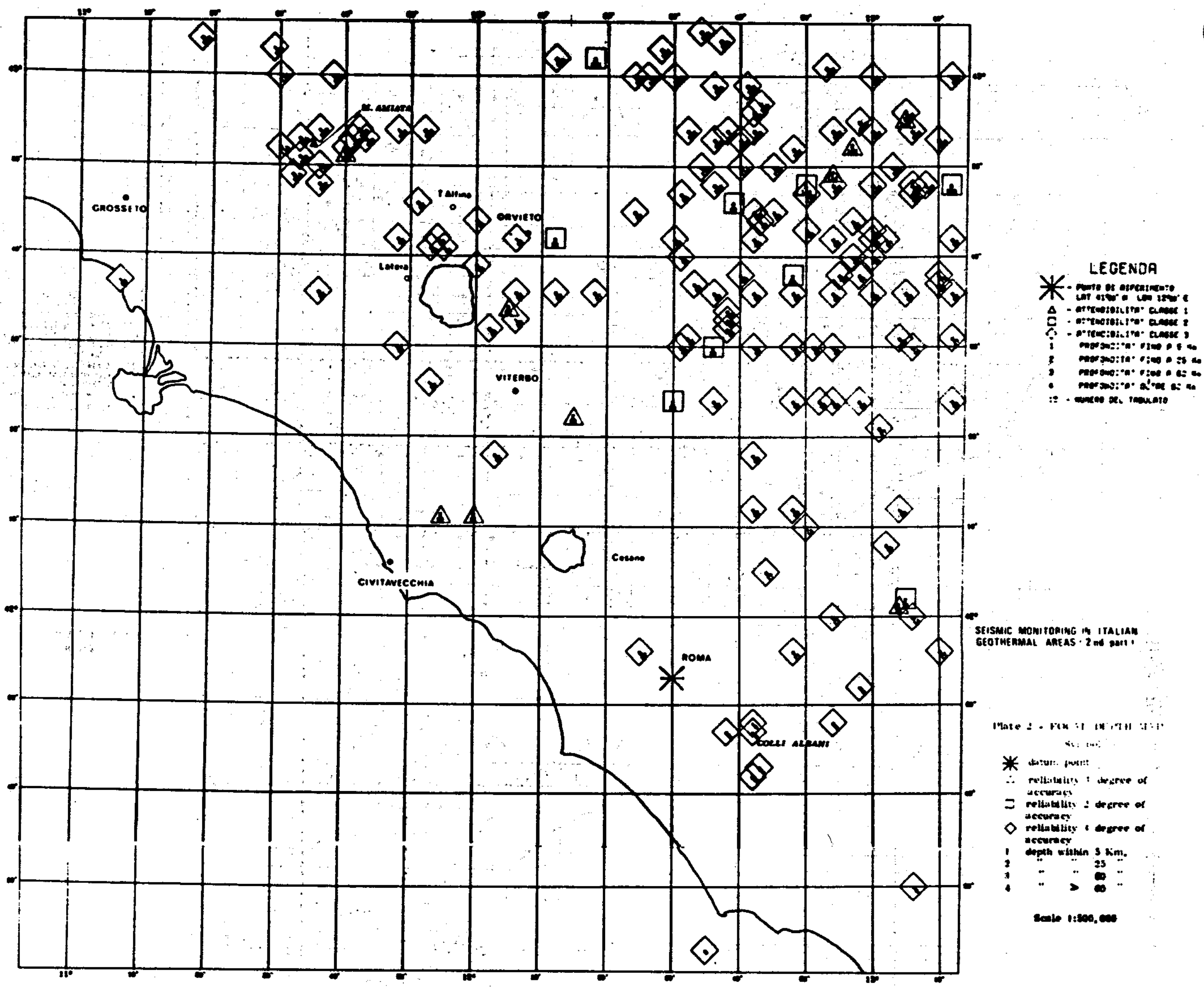

Plate 2. Focal depths.

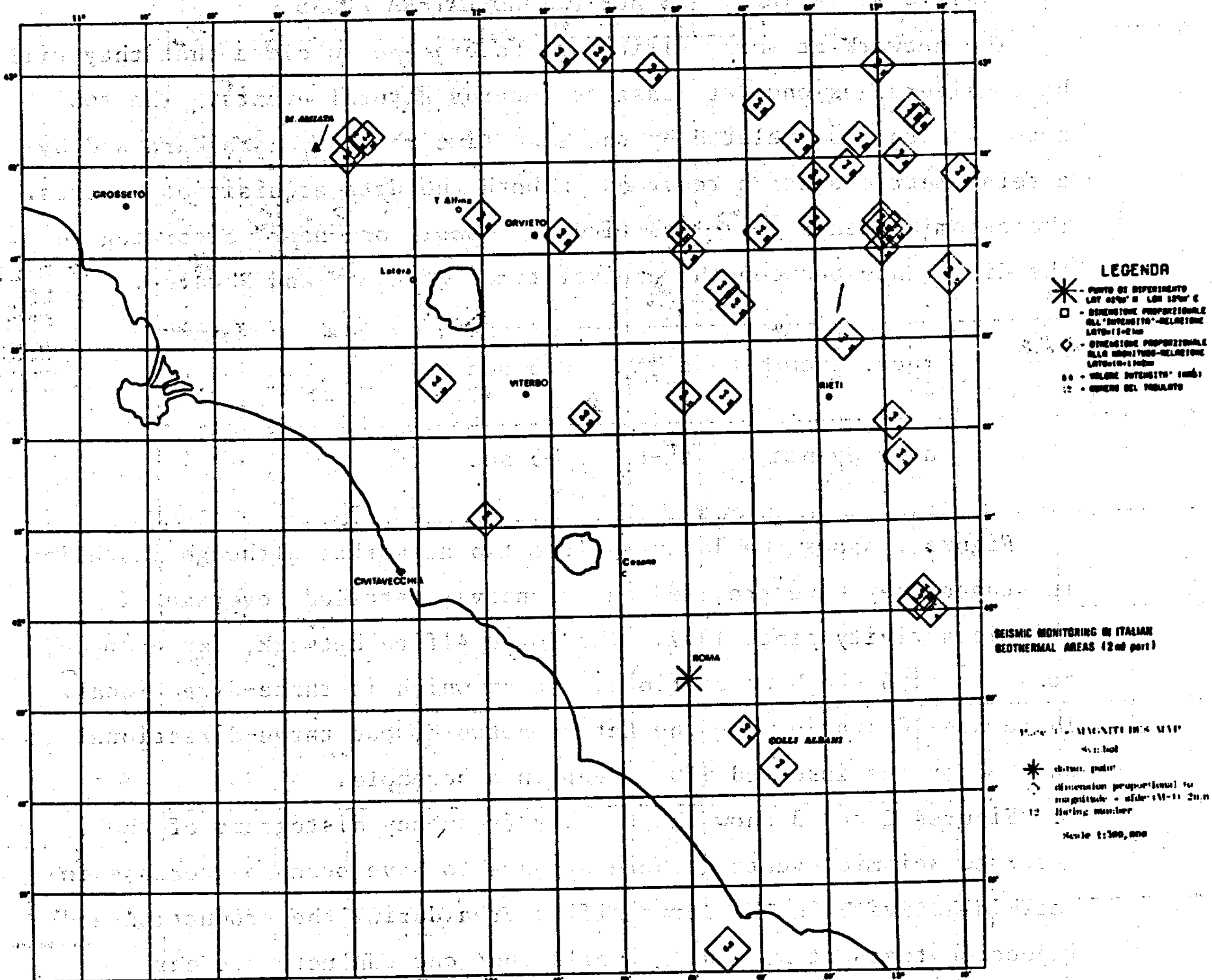

Plate 3. Magnitudes.

3. SEISMICITY IN THE TORRE ALFINA AND LATERA AREAS

The network at Torre Alfina and Latera are so close that they will be considered as one, at least as regards natural events. The two networks are also related by the same time reference standard and by a seismometric station recorded on both the data acquisition centres. The seismic events are classified as "local" or "near" according to the difference between the arrival times of the S and P waves.

local events $t_s - t_p = 0\text{-}3$ sec

near events $t_s - t_p = 3\text{-}5$ sec

Figure 1 shows the layout of the two networks; although installed in stages they have provided an extensive, detailed coverage of seismic activity since 1977. The Torre Alfina network, for example, consists of 6 geophone stations, one of which is three-directional. There are 10 stations on the Latera network, one three-directional and one hydrophone inserted 170 m deep in a borehole.

Figures 2 and 3 show the monthly frequency histograms of the recorded seismic events. There appears to have been no increase in seismic activity in the Torre Alfina area during the production and injection tests at A_{14} and A_4 wells, but one can note a clear correlation between increased activity and specific tests in well L-2 in the Latera area. This aspect will be dealt with later in greater detail.

Not all the recorded events could be processed to determine the focal coordinates as there were some doubts with regard to the first arrivals.

Tables 1 and 2 give the data on the events recorded for the two areas, while Plate 4 presents the distribution of the epicentres, showing magnitude and focal depths projected on a N-S cross-section.

The hypocentres were determined by means of the HYPO 71 computer program, whereas the local magnitude values were calculated with the Cancani-Sieberg equation, valid for Italy:

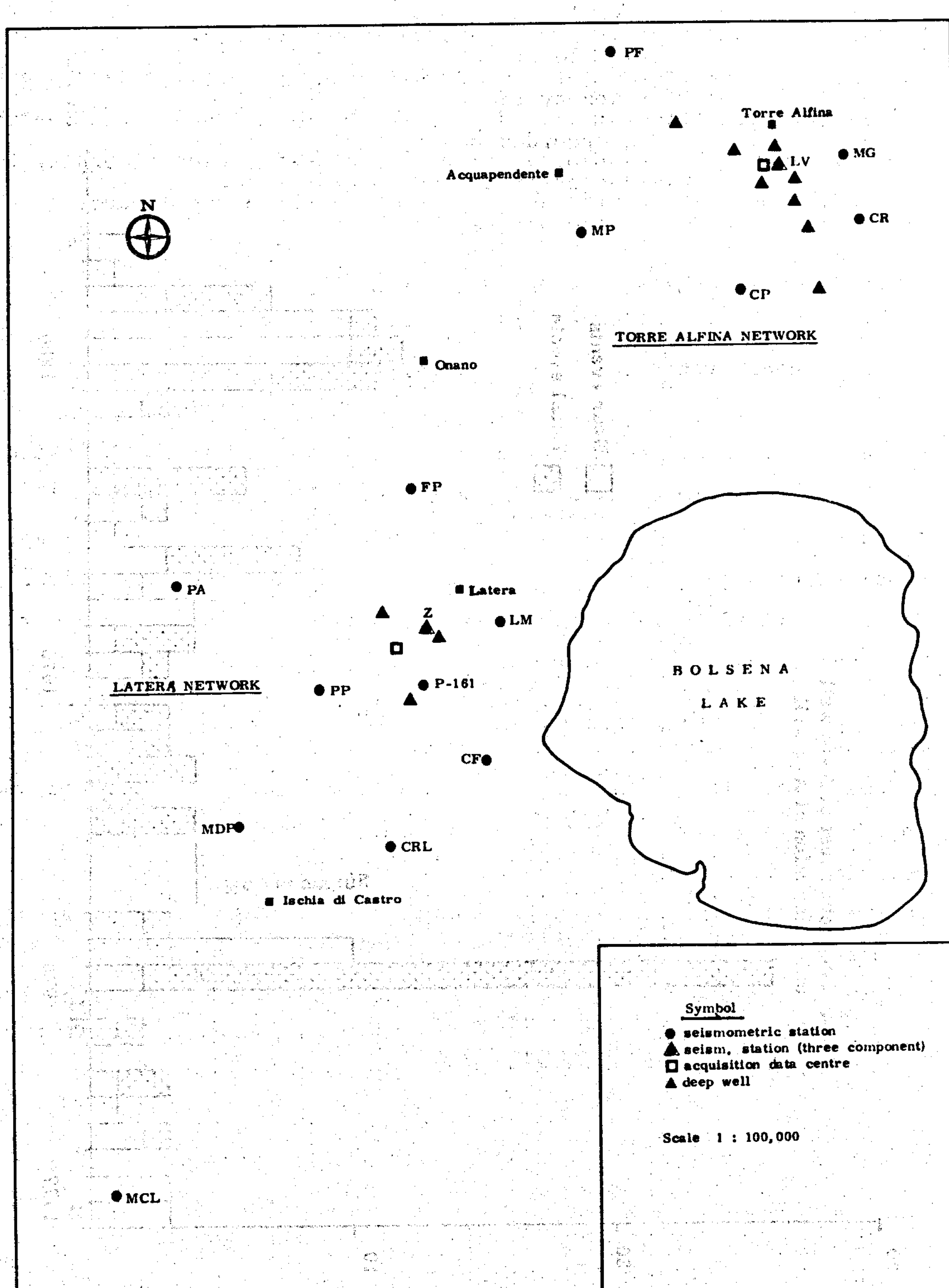

Fig. 1. Torre Alfina and Latera permanent networks.

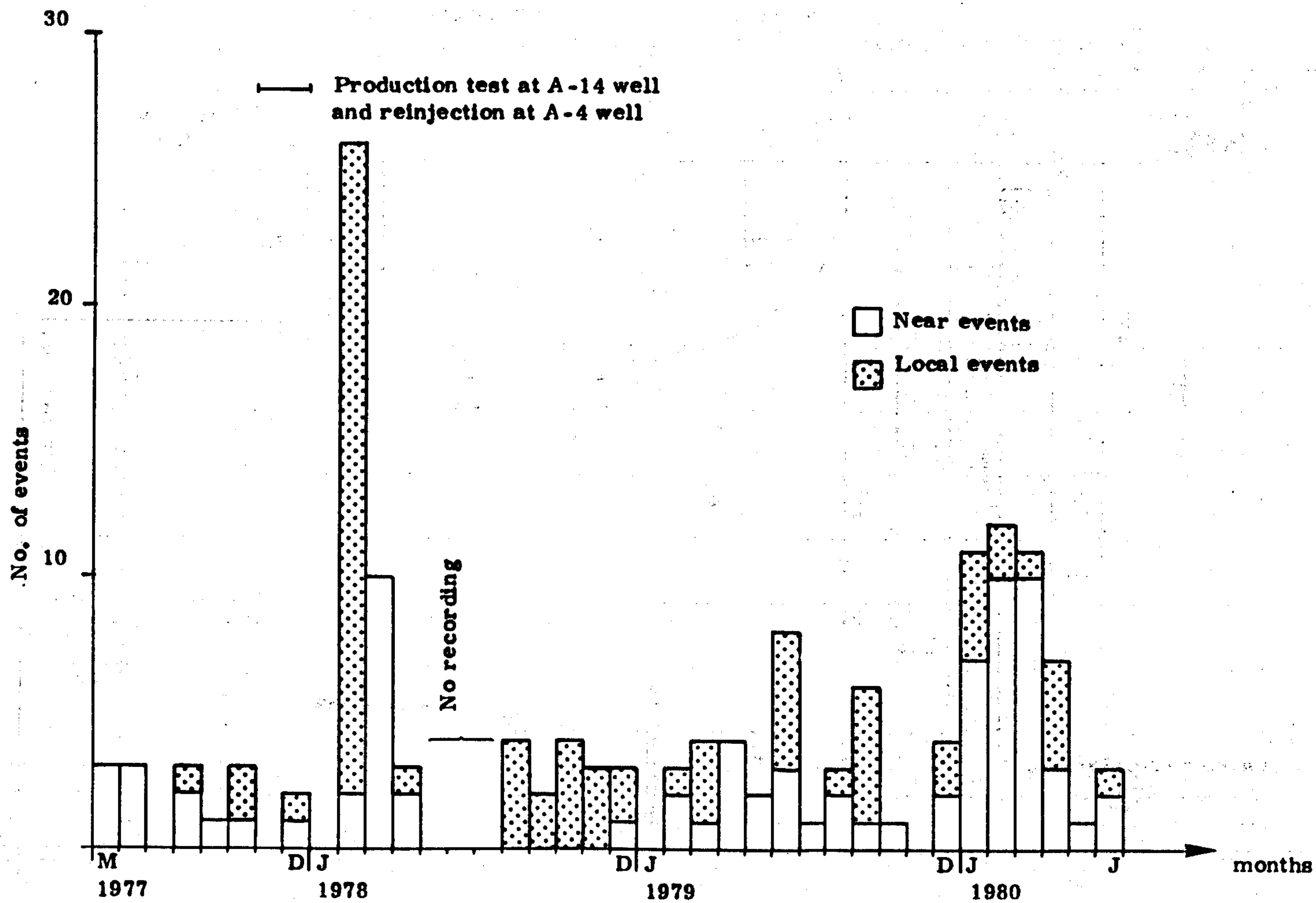

Fig. 2. Torre Alfina area - histogram of seismic events recorded by permanent network.

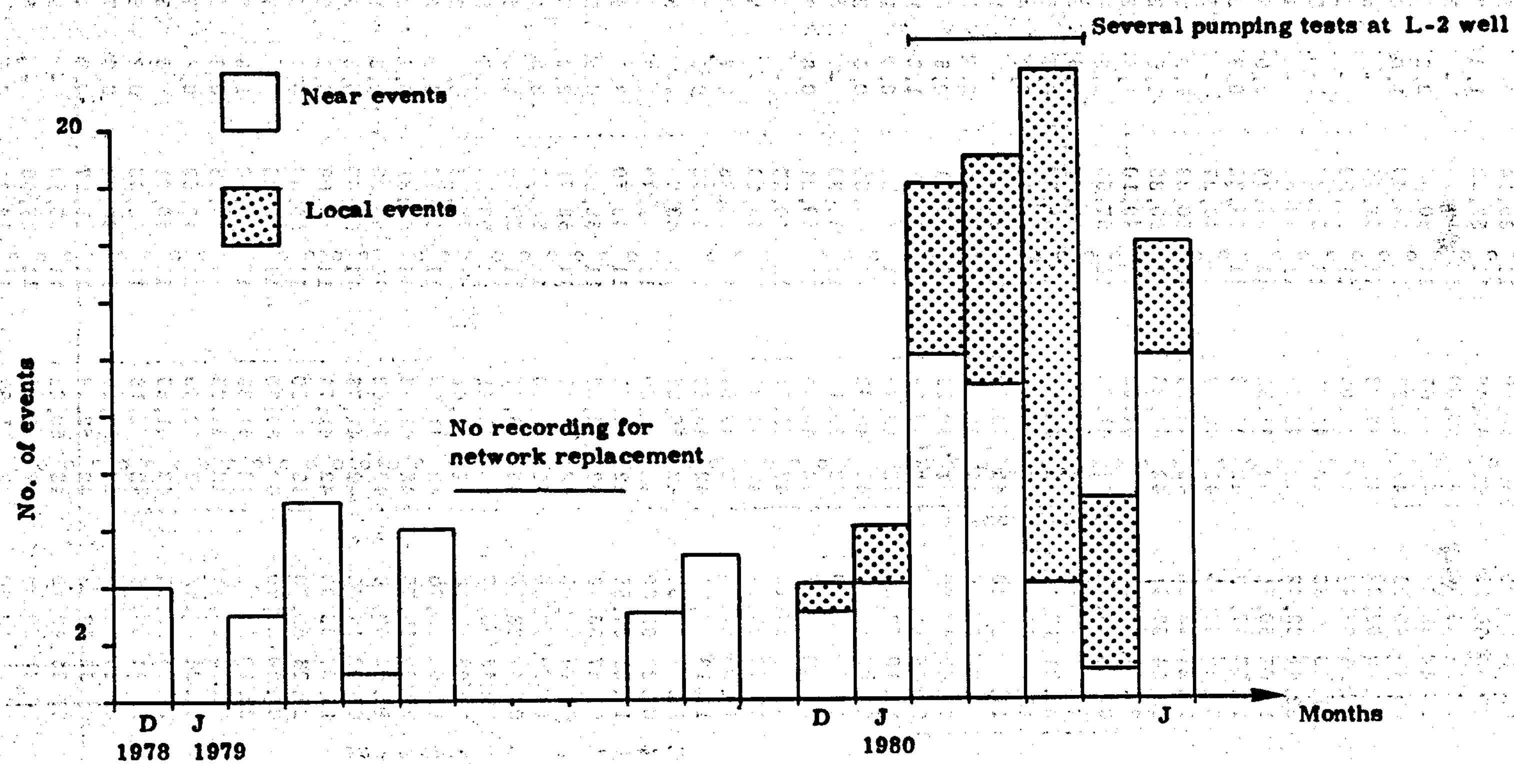

Fig. 3. Latera area - histogram of seismic events recorded by provisional and permanent network.

Table 1. Torre Alfina Earthquakes - Permanent Network.

N°	Date	Origin.	Lat. (N)	Long. (E)	ERH	Z	ERZ	M
11	77.05.25	02.16 20,00	42° 50,00	11° 39,14	-	5,0*	-	0,0
45	77.08.29	06.30 30,14	42° 48,49	11° 52,62	1,2	2,5	0,1	1,0
55	77.09.21	13.36 45,30	42° 57,00	11° 45,14	-	5,0*	-	1,4
69	77.10.21	18.44 39,87	42° 43,67	11° 50,66	2,8	3,6	1,5	1,9
81	77.12.06	02.44 40,15	42° 42,38	11° 58,49	1,0	4,5	0,1	0,6
24	78.02.18	01.25 02,82	42° 42,23	11° 51,65	-	5,0	-	1,5
28	78.02.18	01.28 03,47	42° 42,09	11° 51,59	-	5,0	-	2,0
30	78.02.18	01.29 06,65	42° 41,81	11° 51,87	-	5,0	-	2,0
97	78.03.10	22.41 33,42	42° 48,75	11° 42,54	-	4,5	-	-
168	78.04.23	15.07 50,31	42° 41,59	11° 57,35	3,0	4,0	1,7	1,2
230	78.08.05	17.57 47,46	42° 48,43	11° 54,32	0,9	2,9	0,7	0,4
270	78.08.22	21.22 33,29	42° 42,38	11° 47,27	-	5,2	-	0,1
287	78.08.24	13.24 22,32	42° 44,26	11° 50,33	1,9	2,4	0,3	>1,4
288	78.08.24	13.24 57,91	42° 44,36	11° 50,85	1,5	2,7	0,5	0,9
306	78.09.04	20.31 07,84	42° 41,92	11° 49,10	1,4	3,0	0,5	1,7
333	78.09.16	07.23 47,74	42° 41,02	11° 57,63	0,3	6,4	0,4	>1,6
356	78.10.03	02.26 02,79	42° 40,95	11° 55,72	0,6	5,0	0,5	0,2
374	78.10.12	00.21 17,44	42° 40,59	11° 55,89	0,7	5,6	1,0	0,9
378	78.10.15	16.07 36,97	42° 46,71	11° 49,14	0,2	4,1	0,4	>1,6
379	78.10.15	17.47 23,40	42° 46,69	11° 50,43	-	1,2	-	<0,0
416	78.11.10	09.02 26,37	42° 40,91	11° 57,44	0,5	5,5	0,5	>1,6
417	78.11.10	09.02 42,90	42° 40,26	11° 57,91	0,5	6,1	0,6	1,3
423	78.11.14	02.06 11,08	42° 39,38	11° 55,91	1,2	1,6	0,5	0,8
453	78.12.18	11.19 52,30	42° 43,72	11° 57,62	0,8	1,3	0,6	0,3
458	78.12.21	21.02 01,98	42° 45,63	11° 48,59	0,6	2,4	0,2	0,3
467	78.12.27	11.58 04,90	42° 55,15	11° 50,39	-	5,0	-	-
26	79.02.07	11.22 08,27	42° 43,94	11° 59,24	0,8	2,4	0,2	0,4
30	79.02.09	02.29 57,15	42° 55,71	11° 40,55	-	5,0	-	-
46	79.02.28	18.42 29,97	42° 54,33	11° 42,16	-	5,0	-	-
48	79.03.01	12.02 21,73	42° 43,94	11° 58,23	1,7	2,4	2,7	0,4
59	79.03.12	12.13 57,55	42° 43,88	11° 59,42	0,3	2,3	0,0	0,4
62	79.03.14	13.41 37,56	42° 50,26	11° 43,04	-	5,0	-	-
125	79.04.27	07.30 02,60	42° 53,60	11° 41,70	1,5	5,5	0,3	1,1
158	79.05.28	12.21 37,56	42° 51,73	11° 43,70	3,0	6,4	0,7	0,7
169	79.06.01	05.47 38,46	42° 44,27	11° 52,54	0,5	6,0	0,1	1,8
198	79.06.24	02.14 36,06	42° 47,41	11° 58,71	2,2	8,3	1,4	0,7
200	79.06.24	19.29 42,59	42° 48,90	11° 53,55	2,5	1,0	3,0	0,2
202	79.06.25	08.44 38,55	42° 56,77	11° 50,40	1,3	5,0	5,3	1,6
232	79.08.02	06.45 35,97	42° 42,41	11° 58,23	0,2	5,8	0,3	1,8
239	79.09.20	18.03 47,14	42° 41,61	11° 56,35	0,7	2,6	1,0	1,6
240	79.09.20	18.04 22,73	42° 41,63	11° 56,27	0,6	2,9	0,8	0,8
241	79.09.20	18.09 15,75	42° 41,62	11° 56,31	0,7	2,6	1,0	1,0
242	79.09.20	22.09 57,46	42° 41,62	11° 56,29	0,3	1,9	0,6	1,3
243	79.09.23	08.09 19,33	42° 41,76	11° 55,89	0,5	2,6	0,8	1,3
244	79.09.24	15.07 35,39	42° 41,74	11° 56,08	0,2	0,2	0,1	1,1
464	79.12.16	22.26 52,30	42° 41,50	11° 55,89	0,7	5,9	0,8	1,0
467	79.12.17	06.30 33,70	42° 56,39	11° 45,25	-	7,0	-	1,1
505	79.12.25	22.19 13,65	42° 41,88	12° 12,80	1,8	5,5	0,6	0,4
5	80.01.04	02.56 28,35	42° 41,25	11° 46,96	0,3	5,2	0,5	0,9
26	80.01.20	11.24 03,66	42° 52,45	11° 40,92	0,8	7,3	0,5	1,4
27	80.01.20	14.04 13,40	42° 51,86	11° 40,71	1,0	5,0	0,6	1,3
45	80.01.28	11.24 03,66	42° 52,16	11° 48,63	0,8	6,1	0,5	1,7
110	80.03.15	09.25 42,54	42° 52,16	11° 36,02	2,0	7,6	3,3	1,4
119	80.03.16	01.52 46,23	42° 52,18	11° 35,67	0,8	4,4	0,4	1,6
127	80.03.23	07.35 49,49	42° 50,88	11° 37,10	-	5,9	-	0,4
128	80.03.23	10.21 59,98	42° 50,47	11° 37,06	-	5,8	-	1,5
145	80.04.07	19.18 10,30	42° 41,97	11° 58,31	0,6	5,4	0,7	0,9
146	80.04.07	19.32 32,77	42° 41,98	11° 58,64	0,8	5,2	0,9	1,1
152	80.04.19	23.43 25,11	42° 52,12	11° 40,81	1,3	5,0	0,9	0,6
154	80.04.28	20.16 51,12	42° 46,13	11° 50,18	-	1,3	-	0,8
155	80.04.30	00.53 07,99	42° 50,93	11° 40,34	0,1	6,2	0,8	1,6
167	80.06.02	15.46 09,01	42° 51,13	11° 41,24	2,0	5,0	0,9	1,5

* indicates fixed focal depth solution

Table 2. Latera Earthquakes - Permanent Network.

N°	Date	Origin.		Lat. (N)		Long. (E)		ERH	Z	ERZ	M
13	78.12.12	06.33	29,81	42°	28,11	11°	34,76	8,9	5,0	12,4	1,5
14	78.12.12	06.39	39,96	42°	24,13	11°	35,38	9,8	5,0	14,6	1,5
29	79.02.28	18.42	11,78	42°	53,80	11°	46,10	3,8	5,0	33,9	1,3
31	79.03.02	01.17	59,40	42°	37,99	12°	01,04	2,5	5,3	10,0	0,6
51	79.03.18	12.24	50,46	42°	40,09	11°	58,50	2,4	5,0	6,3	1,3
148	79.05.26	11.20	54,27	42°	31,85	11°	47,26	3,2	5,0	50,5	0,6
155	79.05.28	12.21	55,49	42°	51,23	11°	44,94	1,6	5,0	15,7	0,9
171	79.12.10	23.52	15,76	42°	39,90	11°	44,89	1,0	2,0	4,0	1,6
1	80.01.04	02.56	28,35	42°	41,25	11°	46,96	0,3	5,2	0,5	0,9
40	80.02.20	09.03	37,83	42°	31,99	11°	42,22	1,4	5,0	2,4	1,2
42	80.02.22	23.02	21,12	42°	31,85	11°	42,65	1,3	5,0	2,5	1,7
43	80.02.23	03.00	49,60	42°	32,03	11°	42,42	2,3	5,0	2,8	0,9
44	80.02.23	05.33	53,22	42°	31,97	11°	42,60	2,6	5,0	3,2	0,9
87	80.03.15	11.24	04,27	42°	36,66	11°	49,09	-	0,9	-	1,5
88	80.03.15	12.15	26,14	42°	36,75	11°	49,07	0,3	0,8	0,2	1,8
89	80.03.15	13.59	41,14	42°	36,82	11°	49,09	-	1,2	-	1,7
110	80.03.30	08.00	49,67	42°	36,73	11°	49,06	-	1,2	-	1,7
112	80.04.04	20.23	20,68	42°	36,66	11°	49,07	-	1,0	-	1,6
116	80.04.07	09.38	44,08	42°	37,37	11°	49,49	0,4	2,3	0,7	1,6
117	80.04.07	09.39	31,12	42°	37,41	11°	49,52	0,3	2,2	0,5	1,7
118	80.04.07	09.39	52,22	42°	37,35	11°	49,44	1,1	1,7	1,8	1,7
119	80.04.07	09.40	35,53	42°	37,56	11°	49,58	0,4	3,6	0,7	1,7
120	80.04.07	09.41	16,18	42°	37,30	11°	49,84	-	3,0	-	1,7
125	80.04.09	00.39	11,87	42°	37,32	11°	49,82	-	2,7	-	1,3
130	80.04.12	17.02	31,45	42°	36,80	11°	49,34	-	1,0	-	1,8
131	80.04.14	20.44	55,74	42°	48,15	11°	39,53	1,7	5,0	0,8	1,4
132	80.04.15	21.27	05,77	42°	36,72	11°	49,03	-	1,0	-	1,9
133	80.04.15	21.37	35,07	42°	38,84	11°	48,82	0,3	0,9	0,2	1,8
135	80.04.16	03.32	31,66	42°	36,73	11°	49,05	0,3	0,9	0,2	1,8
144	80.05.04	05.16	20,03	42°	32,86	11°	45,30	0,3	5,8	0,4	1,3
146	80.05.05	01.36	04,56	42°	32,13	11°	43,50	0,4	5,0	0,9	1,2
148	80.05.08	23.07	32,09	48°	32,85	11°	45,32	0,4	6,0	0,4	1,7
149	80.05.09	04.54	24,71	42°	32,94	11°	44,71	0,7	5,9	0,5	1,8
205	80.06.27	22.41	05,20	42°	41,45	11°	55,65	0,4	3,8	0,7	0,6

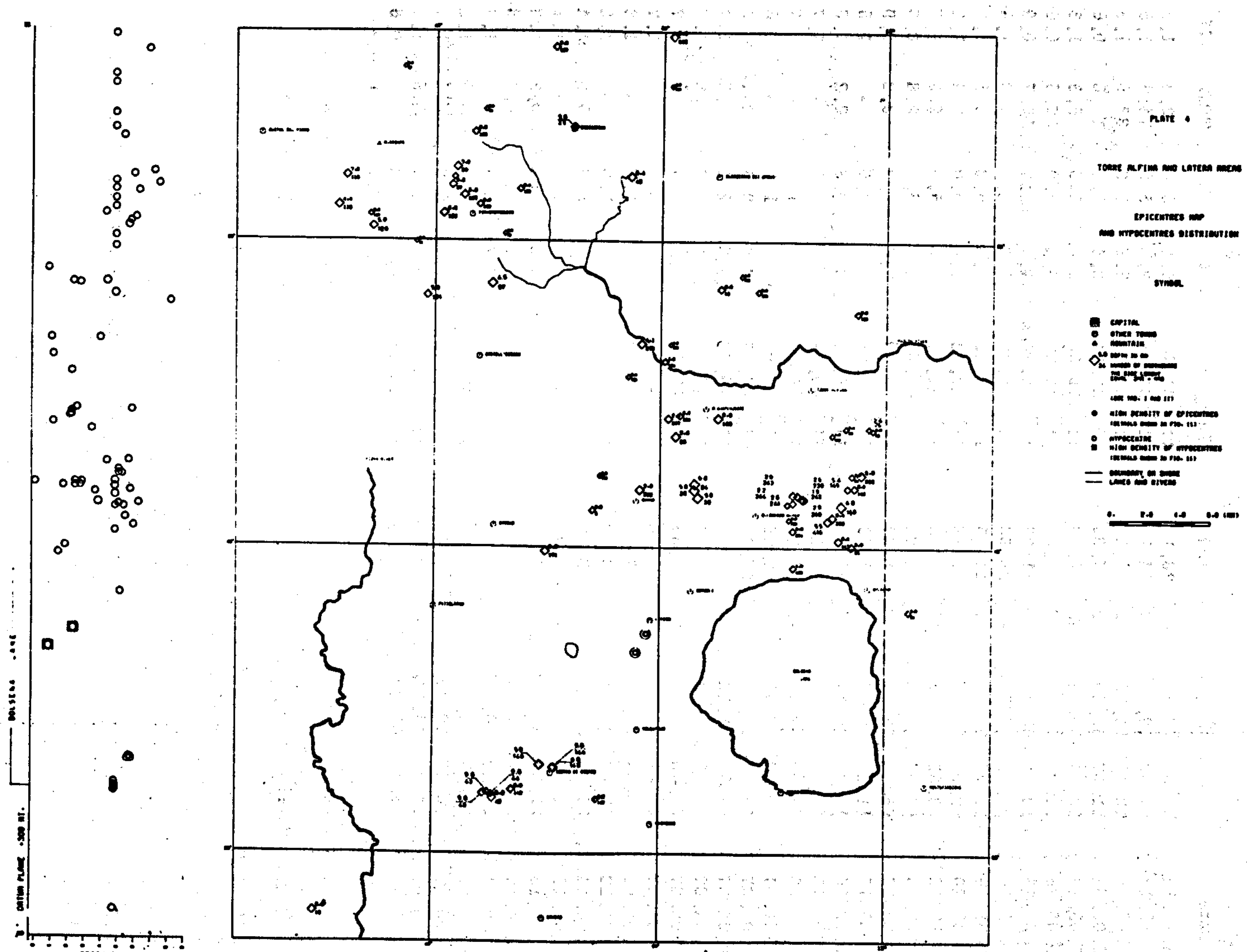

Plate 4. Distribution of epicentres, with magnitude and focal depths projected on N-S cross-section, for Torre Alfina and Latera areas.

$$M = 0.481\ I + 1.407, \text{ for } I\ \text{VII degree}$$

where $I = 3\ (\log a + 1)$ with a = acceleration.

The thickness and velocity of the geoseismic model used in the hypocentre calculations were obtained from available geological and geophysical data. The delay times at the stations were obtained experimentally, using some events occurring relatively near the networks and having known epicentres.

The models used were:

Torre Alfina			Latera		
Layer	Velocity (km/s)	Thickness	Layer	Velocity (km/s)	Thickness
1°	3.0	1.1	1°	2.5	0.165
2°	5.5	1.9	2°	3.4	0.465
3°	6.0		3°	4.0	1.015
			4°	5.3	7.000
			5°	6.2	

The events recorded on both networks referred to the Latera model only, recalculating the delay-times for the Torre Alfina stations.

The epicentral distribution shown in Plate 4 confirms the existence of many historically known seismic centres, such as Castel Giorgio, San Lorenzo, Onano, Aquapendente, Latera, Ischia di Castro and, further north, the Mt. Amiata region. A certain diffuse activity was noted immediately north-west of the Torre Alfina network and, on a much smaller scale, north-east of Bolsena Lake and south of the Latera network.

The magnitude values are generally low, ranging around an average of 1.5. The cross-section reveals that, as far as focal depth is concerned, these events are nearly all quite shallow, ranging between 0 and about 6 km.

3.1 Torre Alfina - Induced Seismicity?

Before the permanent network was installed the seismic activity was monitored between 21st January and 19th March 1977 on a temporary network, during a series of reinjection tests in well RA-1.

Figure 4 shows the daily distribution of events throughout the period in which this network was in operation. An increase in seismic activity is clearly correlated to the two periods of reinjection tests. Figures 5 and 6 give a detailed picture of hourly distribution of these events during these two periods versus the maxima recorded values for ground movements (μ/sec), correlated with the pressure variation curve recorded at well-head and the flow-rate values of the injected water. In both cases the major density of seismic events occurs in correspondence to the highest pressure values, and affecting the pressure curve, flattening it slightly during both the pumping and the pressure re-establishment.

A total of 177 events were recorded, all being identified as seismic signals; the hypocentral coordinates were attainable for 15 of these, as reported in Table 3. Figure 7 shows the epicentral position for the latter, along with the magnitude values, the hypocentral distribution projected on a N-S profile, and the provisional network configuration. Note that the network had only 4 stations, 3 of which were three-directional and very close to one another. They were also rather off-centre with respect to the well and the calculated epicentres.

Nevertheless, it was possible to define the epicentral coordinates with a certain accuracy and, with a little less precision, the depth values; the data were processed with no surface corrections, using the single Torre Alfina - Latera model and the S phase. As the events in most cases saturated all the stations, the maxima of the magnitude values are not always defined.

One can note the following:

a) the distribution of the epicentres around the well;

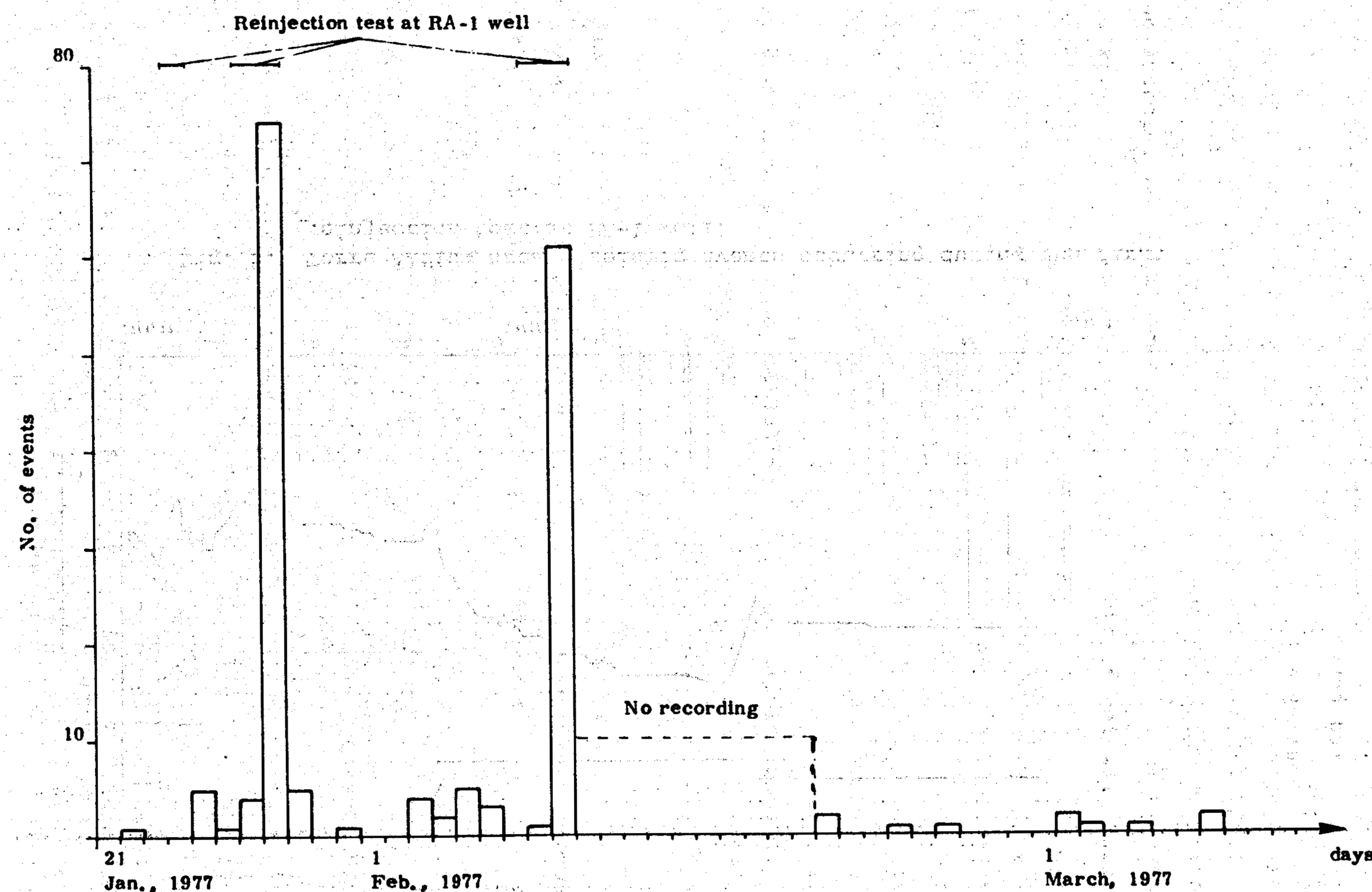

Fig. 4. Torre Alfina area - histogram of seismic events recorded by provisional network during some reinjection tests at RA-1 well.

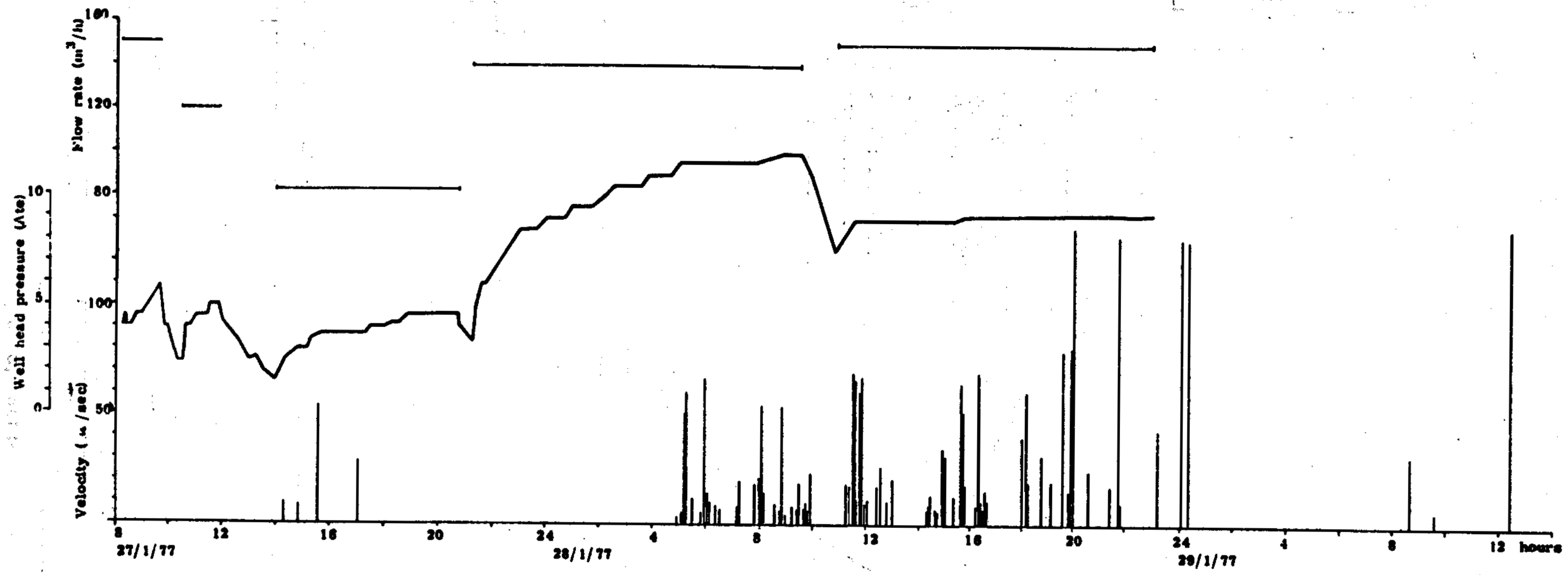

Fig. 5. Torre Alfina area - seismic events occurring during the first reinjection test at RA-1 well.

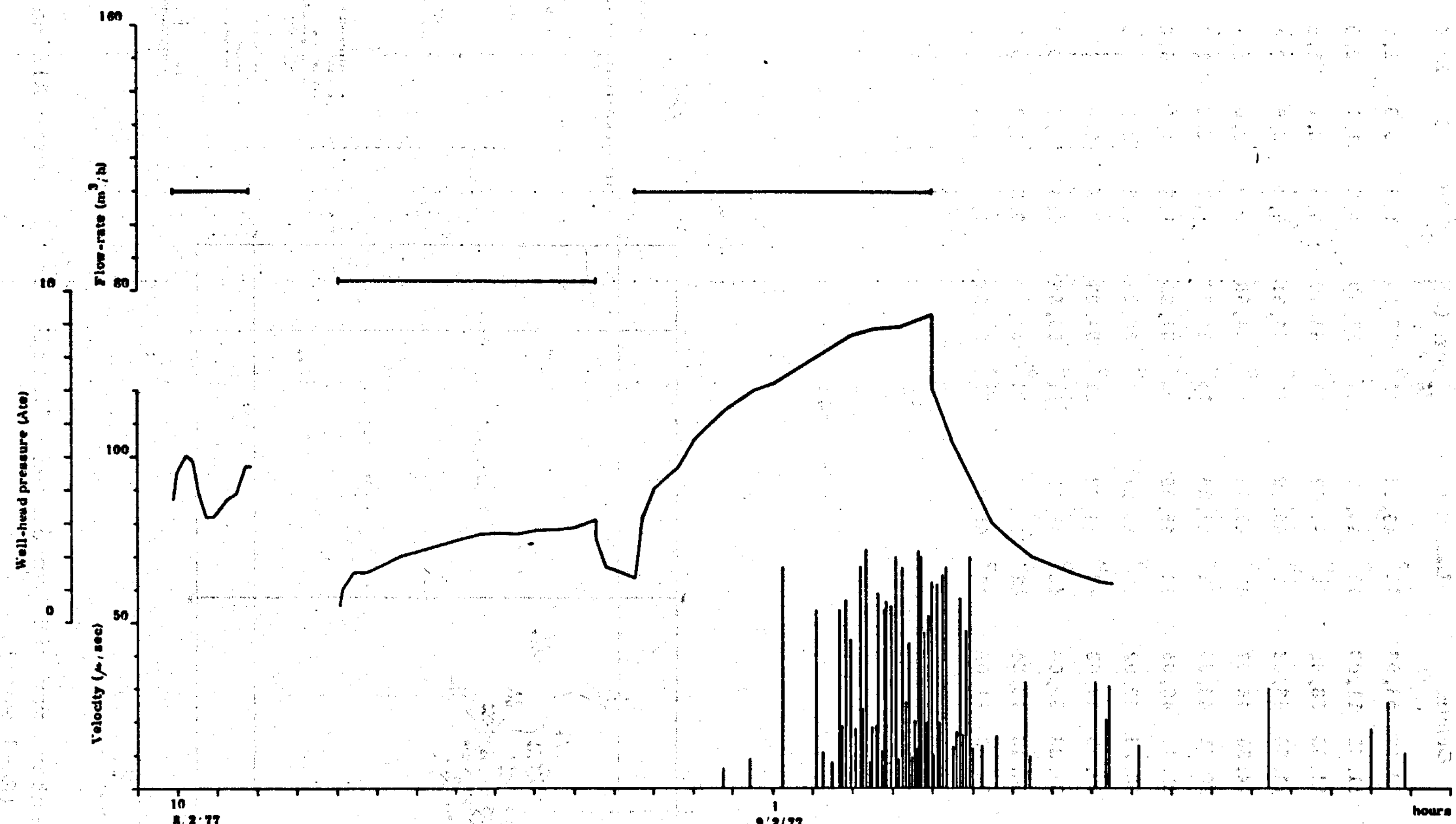

Fig. 6. Torre Alfina area - seismic events occurring during the second reinjection test at RA-1 well.

Table 3. Torre Alfina Earthquakes during Reinjection Test at RA1 Well.

N°	Date	Origin.		Lat. (N)		Long. (E)		ERH	Z	ERZ	M
39/P	77.01.27	09.47	58,98	42°	45,32	11°	55,19	1,8	3,3	1,7	1,1
43/P	77.01.27	11.31	11,00	42°	45,57	11°	54,69	1,2	1,1	9,0	>2,6
44/P	77.01.27	11.35	58,98	42°	45,62	11°	54,70	0,9	2,1	1,8	>2,6
48/P	77.01.27	11.68	46,83	42°	45,59	11°	54,51	0,3	3,6	0,4	1,4
59/P	77.01.27	14.58	46,97	42°	45,42	11°	54,68	0,9	2,6	1,4	2,C
80/P	77.01.27	20.01	45,96	42°	45,25	11°	54,35	1,1	2,2	2,3	>3,C
83/P	77.01.27	21.43	46,95	42°	45,39	11°	54,25	1,2	1,5	6,0	>3,C
119/P	77.02.08	03.23	59,02	42°	45,27	11°	55,04	0,3	3,1	0,2	>2,6
127/P	77.02.08	03.55	47,03	42°	45,32	11°	54,97	0,5	2,8	0,6	2,4
132/P	77.02.08	04.23	59,06	42°	45,61	11°	55,56	0,4	2,9	0,4	2,1
137/P	77.02.08	04.40	46,94	42°	45,23	11°	54,72	0,2	3,3	0,3	>2,5
138/P	77.02.08	04.43	11,09	42°	45,05	11°	54,63	1,0	1,4	4,3	>2,6

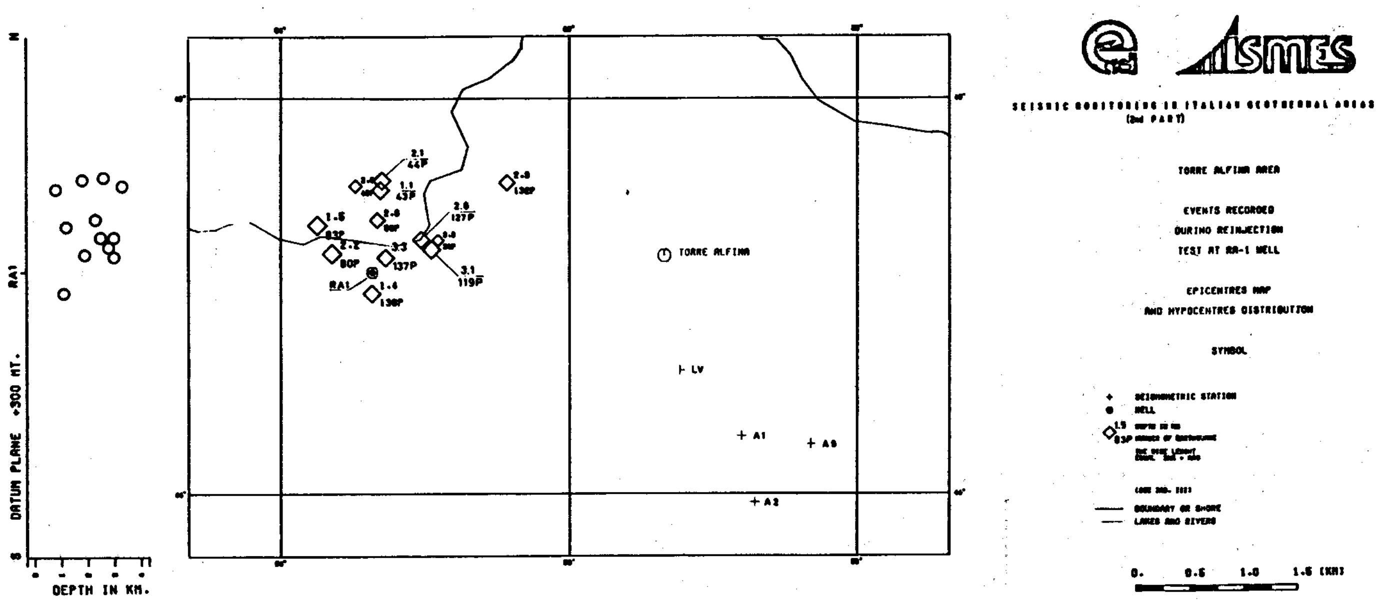

Fig. 7. Epicenters map and hypocenters distribution in Torre Alfina area (RA-1 well).

b) the order of magnitude of the focal depths near the in-hole fractures (2000 m b.s.l.);

c) the maximum magnitude values above even 3.

3.2 Latera - Induced Seismicity?

As mentioned earlier, in reference to Fig. 3, the maximum seismic activity in the Latera area was recorded in well L-2 in March and April 1980, during a series of pumping operations to recover lost equipment.

Figure 8 shows the daily frequency of these seismic events in relation to the cumulative quantities of water injected into the bore. It was impossible to monitor the well-head pressure trend during pumping, except for the initial phase and immediately after operations ended. Figures 9 and 10 give a detailed picture of the events triggered in these two periods, correlating the maximum movement values (μ/sec) with the curve of pressure variation.

These three figures show that an increase in the major seismic activity is connected with the increases in injected volumes of water. In Figs. 9 and 10 in particular the occurrence of the seismic events is clearly accompanied by a flattening of the pressure curve.

Throughout the monitoring period 24 events were recorded, for 15 of which it was possible to determine the focal coordinates (see Table 4). Figure 11 represents the epicentral distribution, with the magnitude values and the hypocentral distribution projected onto a N-S cross-section. This figure indicates that:

a) all the events lie along a NE-SW alignment passing through well L-2;

b) the magnitude values range between 1.5 and 2;

c) the events can be grouped into two well-defined areas of differing focal depth; the first is right next to the well, with a depth of less than 1 km and the second further away with a maximum depth of 2 km.

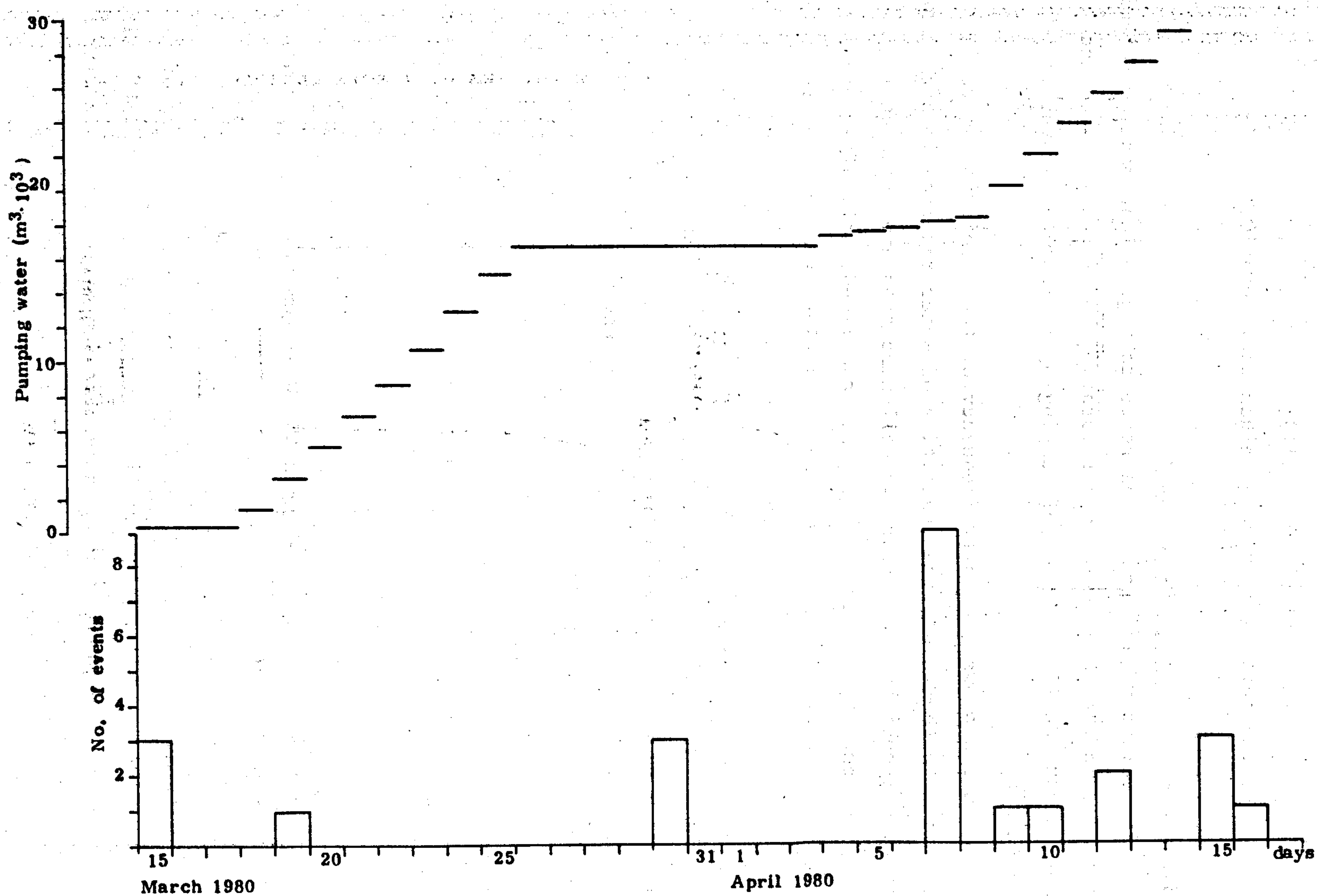

Fig. 8. Latera area - histogram of seismic events recorded by permanent network during pumping operations at L-2 well.

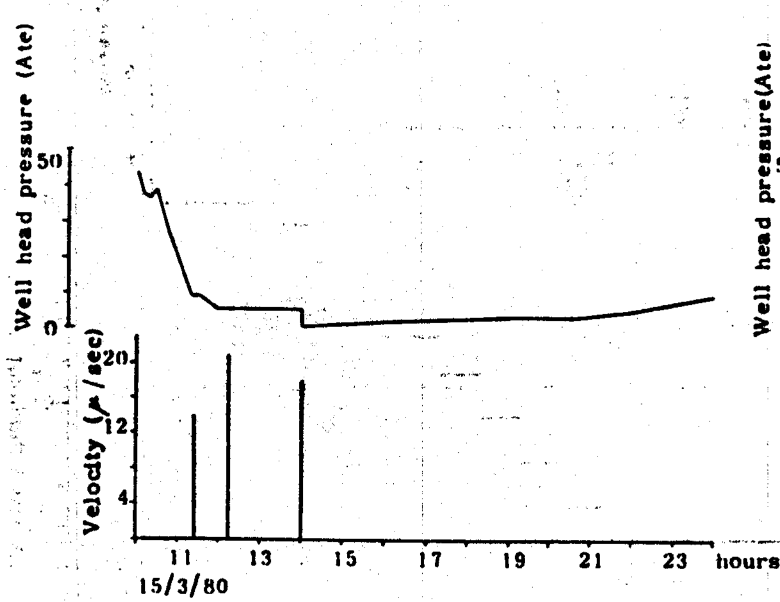

Fig. 9. Latera area - seismic events occuring during the first reinjection phase at L-2 well. (Average flow rate was 100 m^3/h.)

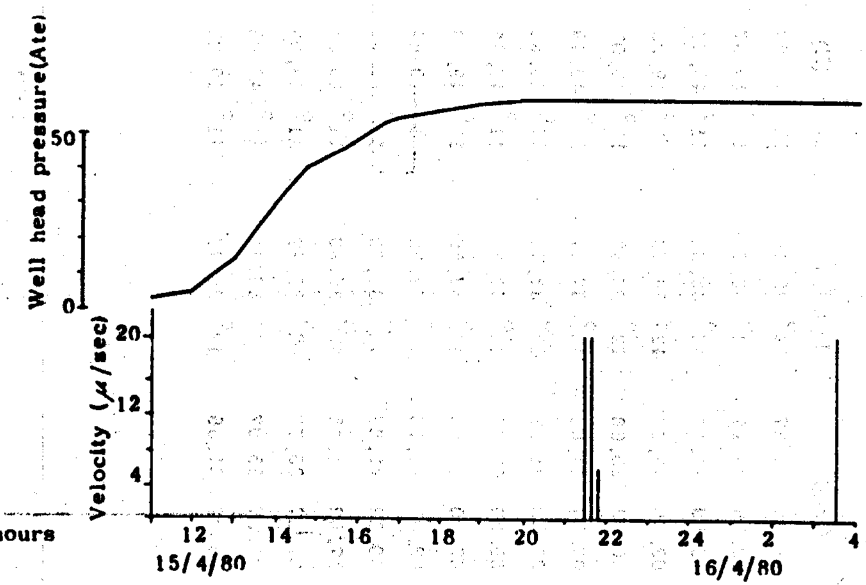

Fig. 10. Latera area - seismic events occurring after shut-in of L-2 well.

Table 4. Latera Earthquakes during Pumping Test at L2 Well.

N°	Date	Origin		Lat. (N)	Long. (E)	ERH	Z	ERZ	M
87	80.03.15	11.24	04,27	42° 36,66	11° 49,09	-	0,9	-	1,5
88	80.03.15	12.15	26,14	42° 36,75	11° 49,07	0,3	0,8	0,2	1,8
89	80.03.15	13.59	41,14	42° 36,82	11° 49,09	-	1,2	-	1,7
110	80.03.30	08.00	49,67	42° 36,73	11° 49,08	-	1,2	-	1,7
112	80.04.04	20.23	20,68	42° 36,66	11° 49,07	-	1,0	-	1,6
116	80.04.07	09.38	44,08	42° 37,37	11° 49,49	0,4	2,3	0,7	1,6
117	80.04.07	09.39	31,12	42° 37,41	11° 49,52	0,3	2,2	0,5	1,7
118	80.04.07	09.39	52,22	42° 37,35	11° 49,44	1,1	1,7	1,8	1,7
119	80.04.07	09.40	35,53	42° 37,56	11° 49,58	0,4	3,6	0,7	1,7
120	80.04.07	09.41	16,18	42° 37,30	11° 49,84	-	3,0	-	1,7
125	80.04.09	00.39	11,87	42° 37,32	11° 49,82	-	2,7	-	1,3
130	80.04.12	17.02	31,45	42° 36,80	11° 49,34	-	1,0	-	1,8
132	80.04.15	21.27	05,77	42° 36,72	11° 49,03	-	1,0	-	1,9
133	80.04.15	21.37	35,07	42° 38,84	11° 48,82	0,3	0,9	0,2	1,8
135	80.04.16	03.32	31,66	42° 36,73	11° 49,05	0,3	0,9	0,2	1,8

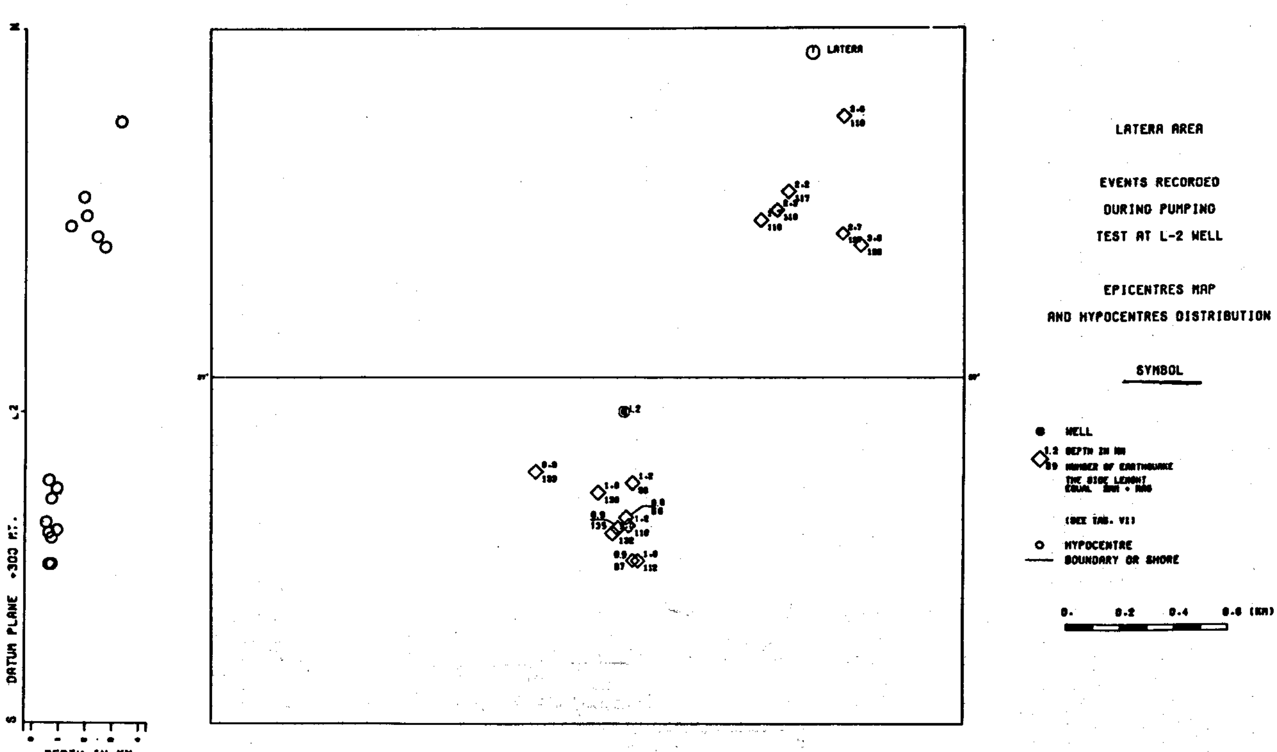

Fig. 11. Latera area - events recorded during pumping test at L-2 well.

4. SEISMIC ACTIVITY AT CESANO

The seismic activity in Cesano area was monitored in two separate phases and on two different networks.

During the first phase, between 5th May and 6th June 1978, a provisional network was used, with 5 seismometric stations connected by cable to the data acquisition centre. This network was installed very near well RC-1 during a series of reinjection tests.

Since 9th March 1979, a permanent telemetered network has been in operation consisting of 7 seismometric stations including one three-component.

4.1 Cesano - Induced Seismicity?

Figure 12 shows the daily frequency of events during operation of the provisional network. The seismic activity clearly intensifies during three periods of injection tests. The triggering of these events during these three periods is shown in Figs. 13 and 14, with the maximum ground movement values (μ/sec) correlated with the curve of pressure variation at well-head.

In the first case (period from 9 to 10 May 1978) the seismic events can be correlated with a certain pressure threshold, while in the second phase the greatest concentration of seismic events occurs during a gradual increase in pressure, about 24 hours after injection began.

Throughout the period a total of 36 seismic events were recorded; the epicentres were determined for 11 of these, as shown in Table 5. This being a densely populated area with a strong background noise of artificial origin during the daytime period, it was somewhat difficult to obtain an accurate estimate of the first arrivals of the P wave, in at least 4 stations. The epicentral coordinates were therefore obtained by a series of calculations, assuming as a fixed hypocentral depth the absorption depth in the well of the injected water.

The geoseismic model used, relative to a depth of 200 m b.s.l., is as follows:

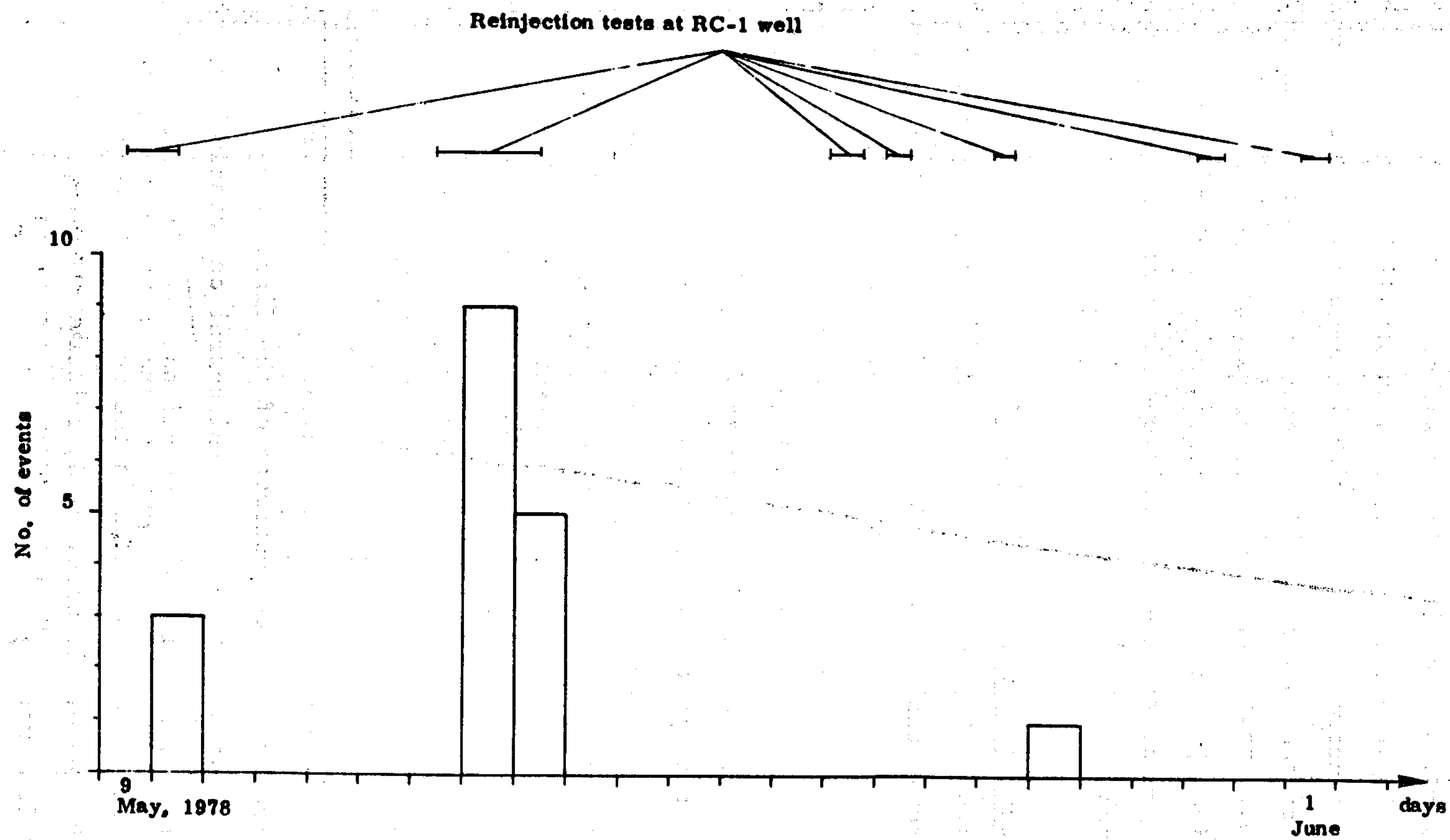

Fig. 12. Cesano area - histogram of seismic events recorded by provisional network during several reinjection tests at RC-1 well.

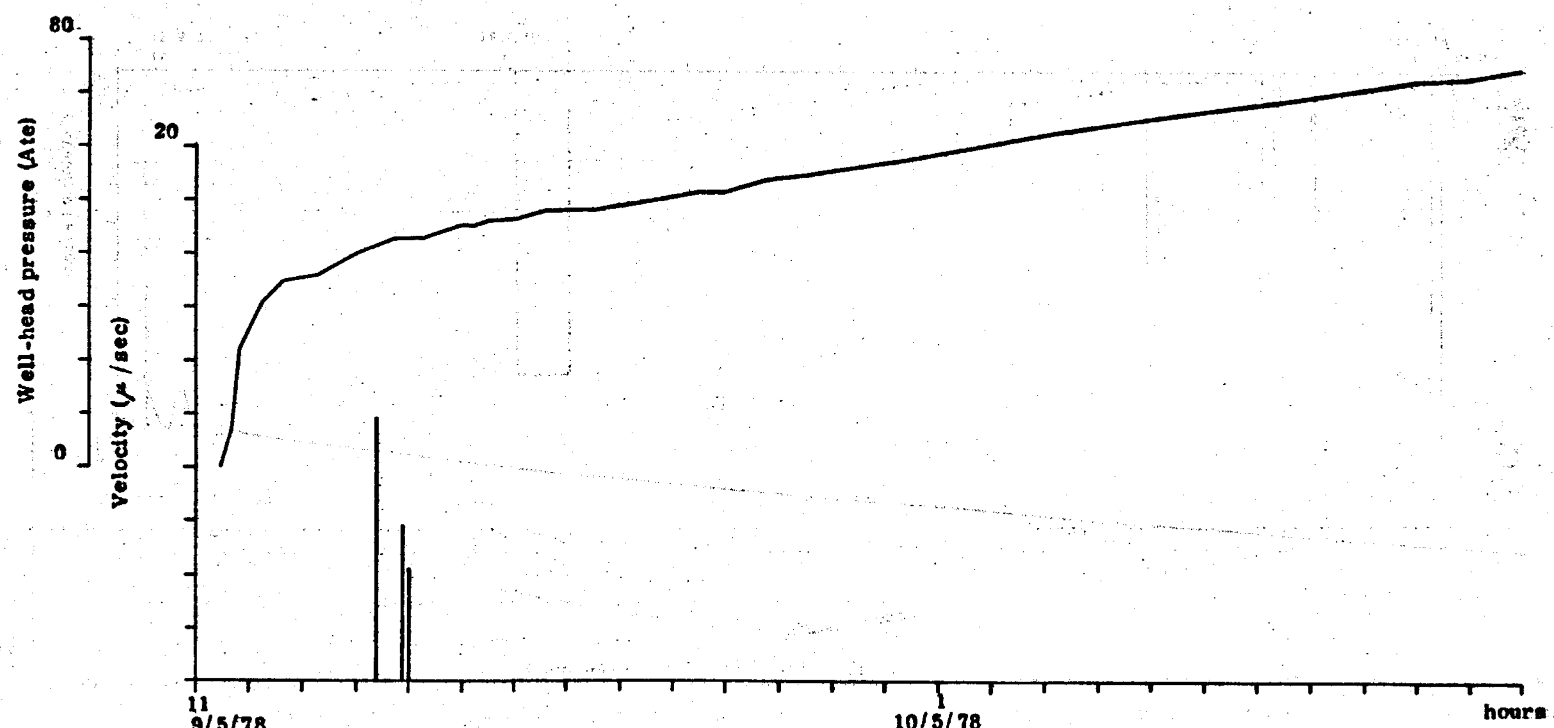

Fig. 13. Cesano area - seismic evnts occurring during first reinjection test at RC-1 well. (Average flow-rate was 100 m^3/h).

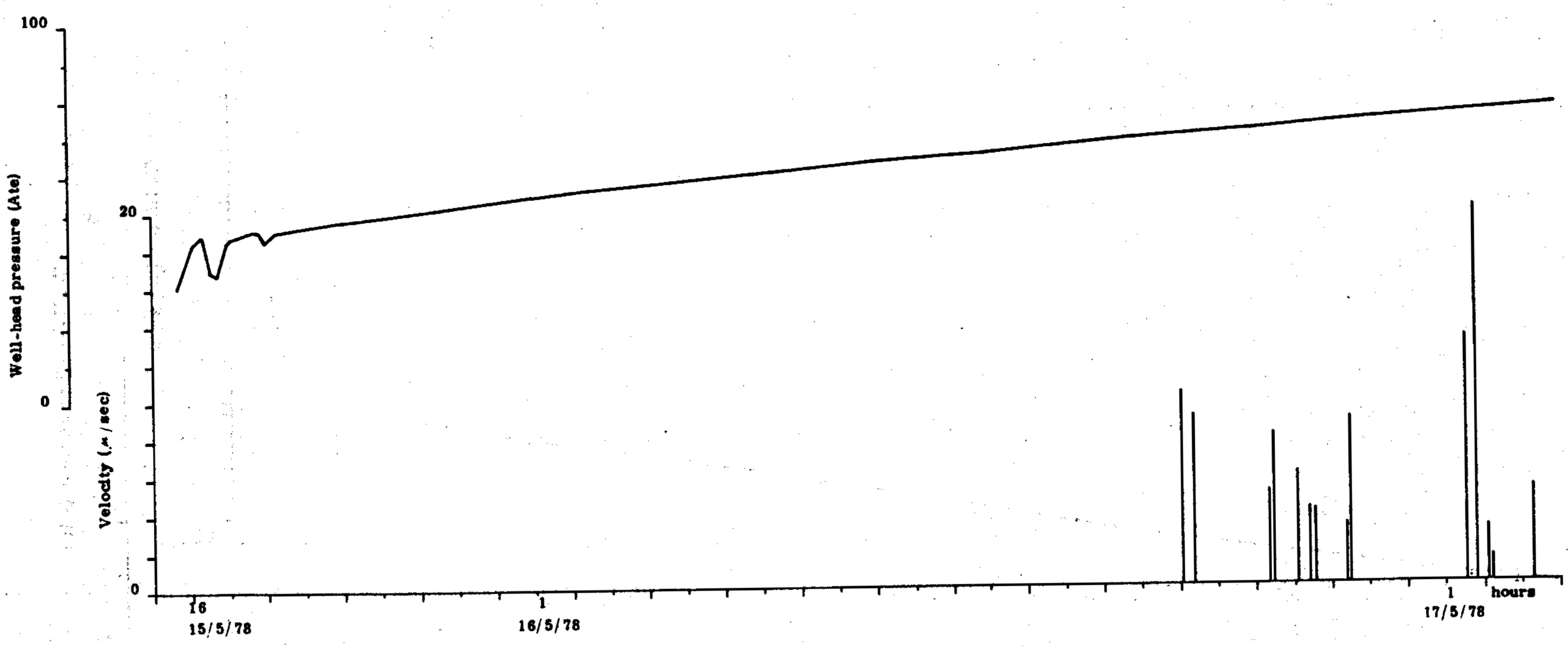

Fig. 14. Cesano area - seismic events occurring during second reinjection test at RC-1 well. (Average flow-rate was 55 m^3/h).

Table 5. Cesano Earthquakes during Reinjection Test at RCl Well.

N°	Date	Origin.		Lat. (N)		Long. (E)		ERH	Z	ERZ	M
3	78.05.10	14.22	01,18	42°	06,57	12°	22,76	1,7	1,5*	1,9	1,6
5	78.05.10	14.58	59,98	42°	06,63	12°	22,57	-	1,5*	-	1,1
14	78.05.16	18.03	00,06	42°	06,57	12°	22,96	-	1,5*	-	1,8
15	78.05.16	18.22	00,44	42°	06,67	12°	22,57	1,7	1,5*	2,2	1,5
17	78.05.16	20.27	00,55	42°	06,61	12°	22,59	-	1,5*	-	1,5
18	78.05.16	21.05	00,33	42°	06,64	12°	22,76	0,3	1,5*	0,3	1,2
21	78.05.16	22.24	00,11	42°	06,70	12°	22,53	-	1,5*	-	0,9
22	78.05.17	22.28	00,55	42°	06,59	12°	22,54	0,0	1,5*	0,0	1,5
23	78.05.17	01.40	00,38	42°	06,69	12°	22,64	-	1,5*	-	1,8
24	78.05.17	01.52	00,41	42°	06,65	12°	22,60	-	1,5*	-	2,0
25	78.05.17	02.09	00,54	42°	06,62	12°	22,61	-	1,5*	-	0,9

* indicates fixed focal depth solution

Table 6. Cesano Earthquakes - Permanent Network.

N°	Date	Origin.		Lat. (N)		Long. (E)		ERH	Z	ERZ	M
121	79.05.21	16.54	01,82	42°	05,87	12°	27,12	1,5	9,8	1,1	>1,9
122	79.05.21	17.29	52,82	42°	06,32	12°	28,07	1,3	12,4	0,7	>1,6
154	79.06.17	22.41	20,92	42°	03,53	12°	25,52	3,2	13,2	1,9	0,66
200	79.07.07	18.29	07,52	42°	11,37	12°	27,38	1,7	8,1	2,3	>1,4
310	79.09.15	05.19	26,21	42°	04,33	12°	27,07	5,6	10,5	3,1	1,0
315	79.09.30	19.56	02,61	41°	59,83	12°	29,12	3,3	17,6	2,0	0,5
495	79.11.05	22.11	11,61	42°	13,67	12°	30,24	3,9	16,8	3,3	1,2
583	79.11.24	05.27	45,79	42°	05,94	12°	30,28	1,2	10,6	0,9	1,2
584	79.11.24	11.47	05,26	42°	03,15	12°	26,21	2,9	11,6	1,5	1,5
614	79.12.07	05.18	05,72	42°	02,15	12°	26,50	0,8	8,7	0,8	0,9
616	79.12.08	00.50	19,37	42°	04,26	12°	27,24	2,3	14,1	1,0	-0,1
282	80.05.23	17.51	16,11	42°	07,81	12°	25,32	0,4	6,4	0,4	1,6

Layer	Velocity (km/s)	Thickness (km)
1^o	3.2	1.5
2^o	5.5	

Considering how near the stations are to well RC-1, the model was based on well stratigraphy and the sonic logs. The epicentres vary slightly with a variation in the hypocentral depth from 1.5 to 1.7 km. Figure 15 shows the network configuration, together with the epicentral distribution for both solutions and the magnitude values.

Note that:

a) in the first case, with a focal depth of 1.5 km, the epicentres are concentrated in a small area immediately south-west of well RC-1;

b) in the second case, with a depth of 1.7, they tend to lie along a NW-SE belt passing through the displacement with the same trend, individualized by some surface geophysical and geological surveys;

c) all the events have magnitude values between 1 and 2.

4.2 Cesano - Natural Seismicity

The monthly frequency of the events recorded on the permanent network is shown in the histogram of Fig. 16. The latter shows that in the period in question there was little activity in the area and no particular increase in seismic activity during a production and injection test in well C-5.

As with Torre Alfina and Latera areas, the recorded seismic events were classified as "local" or "near" according to the difference between the arrival times of the S and P waves.

The geoseismic model used for the permanent network is as follows:

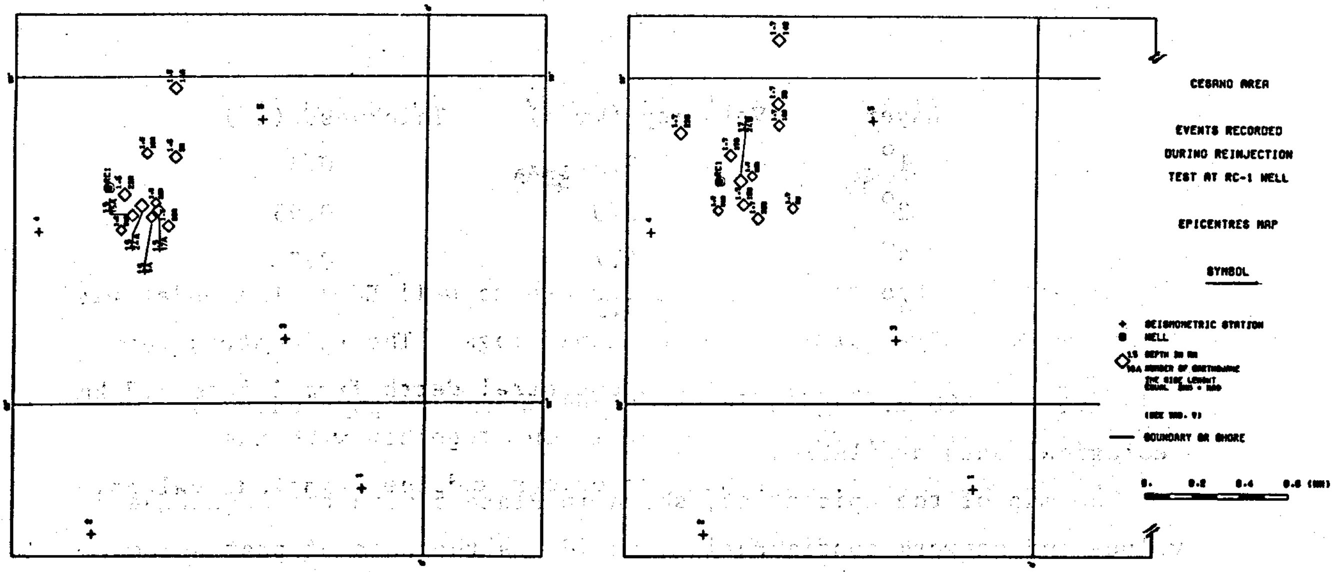

Fig. 15. Cesano area - events recorded during reinjection test at RC-1 well.

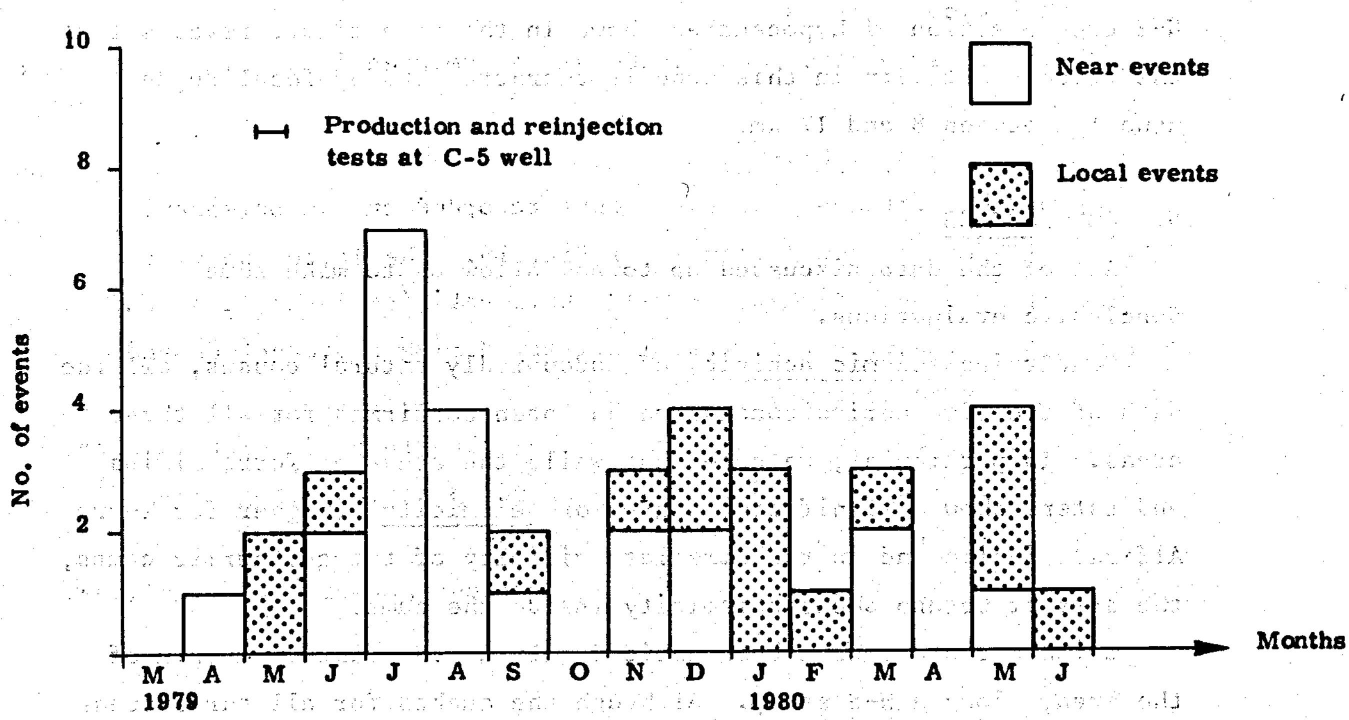

Fig. 16. Cesano area - histogram of seismic events recorded by permanent network.

Layer	Velocity (km/s)	Thickness (km)
1°	2.5	0.4
2°	3.0	0.95
3°	4.7	0.5
4°	5.5	

relative to +300 m.; again it was based on the geophysical and geological data available.

The map of the epicentres, shown in Plate 5 with the magnitude values and network configuration, validates the data of past seismic activity, revealing a low degree of seismicity in the Cesano geothermal area and a cluster of events along a roughly N-S belt east of the area.

The magnitudes, again calculated from the Cancani-Sieberg equation, reach values of more than 1.95.

As all the events were some distance away from the network, the figure shows only those whose coordinates could be determined. The N-S cross-section of hypocentres shown in the same figure reveals that the seismic activity in this zone is characterized by focal depths usually between 8 and 17 km.

5. CONCLUSIONS

All of the data discussed up to now allow us to make some conclusive evaluations.

Concerning seismic activity of undoubtedly natural causes, all the data of the time period considered has been confirmed for all three areas. In particular, we note that while the areas of Torre Alfina and Latera show a significant degree of seismicity, (higher for Torre Alfina), inside and in the immediate vicinity of the geothermic camps, the area of Cesano shows seismicity inside the camp.

Seismic centers have been noticed only at the eastern margin of the area, along a N-S strip. Although the quakes for all three areas have an undoubtedly superficial origin, in Cesano the focal depths are greater.

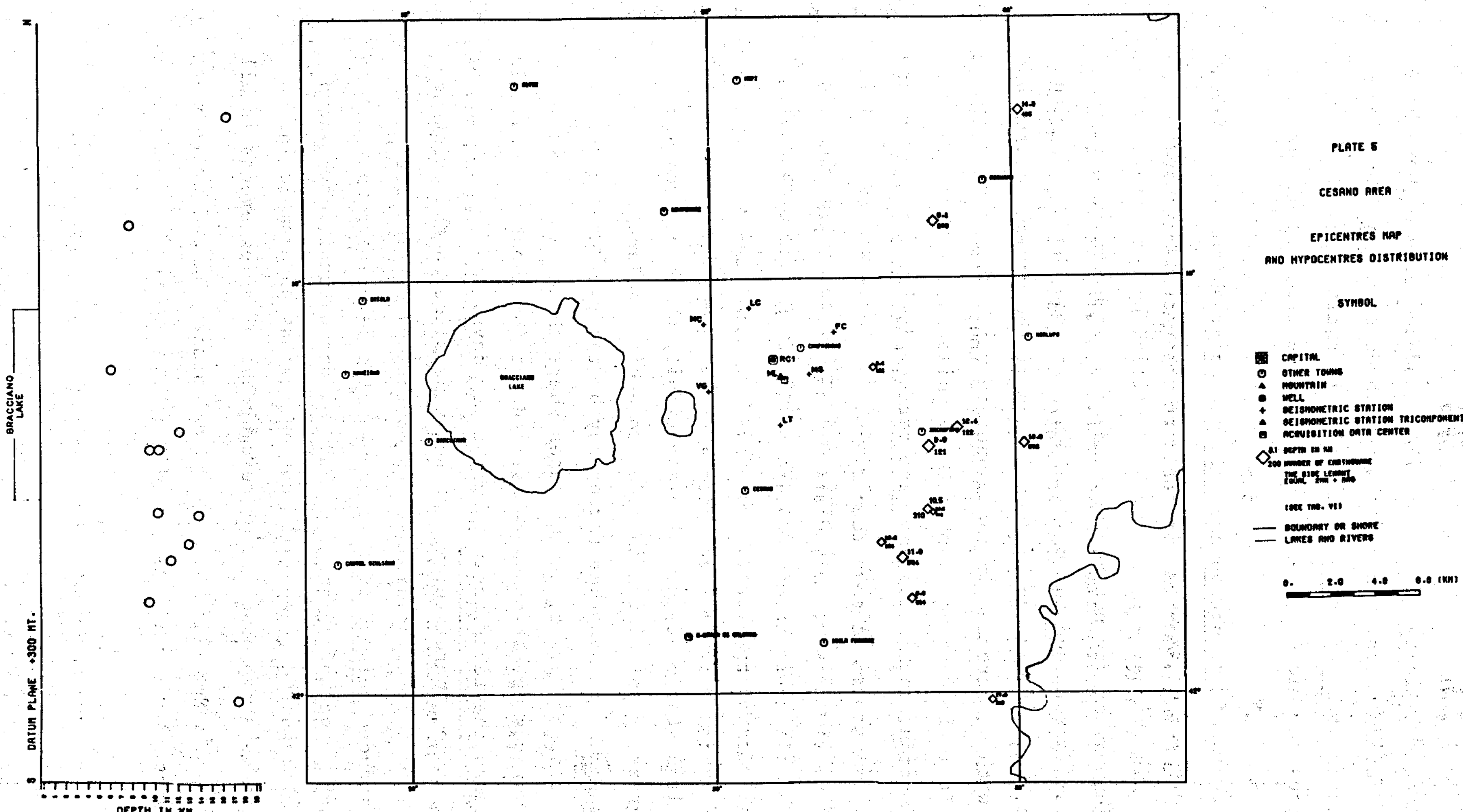

Plate 5. Distribution of epicentres, with magnitude and focal depths projected on N-S cross-section, for Cesano area.

Concerning seismicity of a very likely induced origin there have been contradictory cases. In fact, it has been seen that in connection with tests of reinjection and pumping in shafts RA-I, L-2, and RC-1, numerous seismic events have risen in the vicinity of the shafts.

During tests of production and reinjection at shafts A-14, A-4, and C-5, there was no evidence of any intensification of seismic activity. This triple response may be justified by a multiplicity of factors which may or may not be independent of each other.

The first factor, and the most conditioning one, has to do with the diverse thermo-fluid-dynamic conditions of the various shafts and the second with differences in the manner in which the tests were executed. It is in fact noteworthy that, while in the three cases of seismic induction, the injections were performed with clear water and pressure, in shaft A-4 the fluid extracted from A-14 was injected in a free-flowing manner; the test performed at C-5 consisted first in the emptying of the shaft, followed by injection of the same fluid which had been extracted.

Another factor may be the presence, in the vicinity of the shafts, of more or less stable structural discontinuity which may require varying degrees of soliciting in order to achieve a lack of equilibrium. Finally, another factor may be the time needed to perform the tests; in fact, in the cases where there was a seismic effect the various operations were carried out for about a month. In the other cases the tests covered only a few days.

At this stage, therefore, we can not generalize on the existence of a cause-effect relationship between operations carried out in shafts and induced seismicity. It should also be pointed out that in all areas both types of seismicity, induced and natural, have shown low values of magnitude, generally not over a; as an example in Plate 6 there is a reproduction of seismograms of a few events in all three areas.

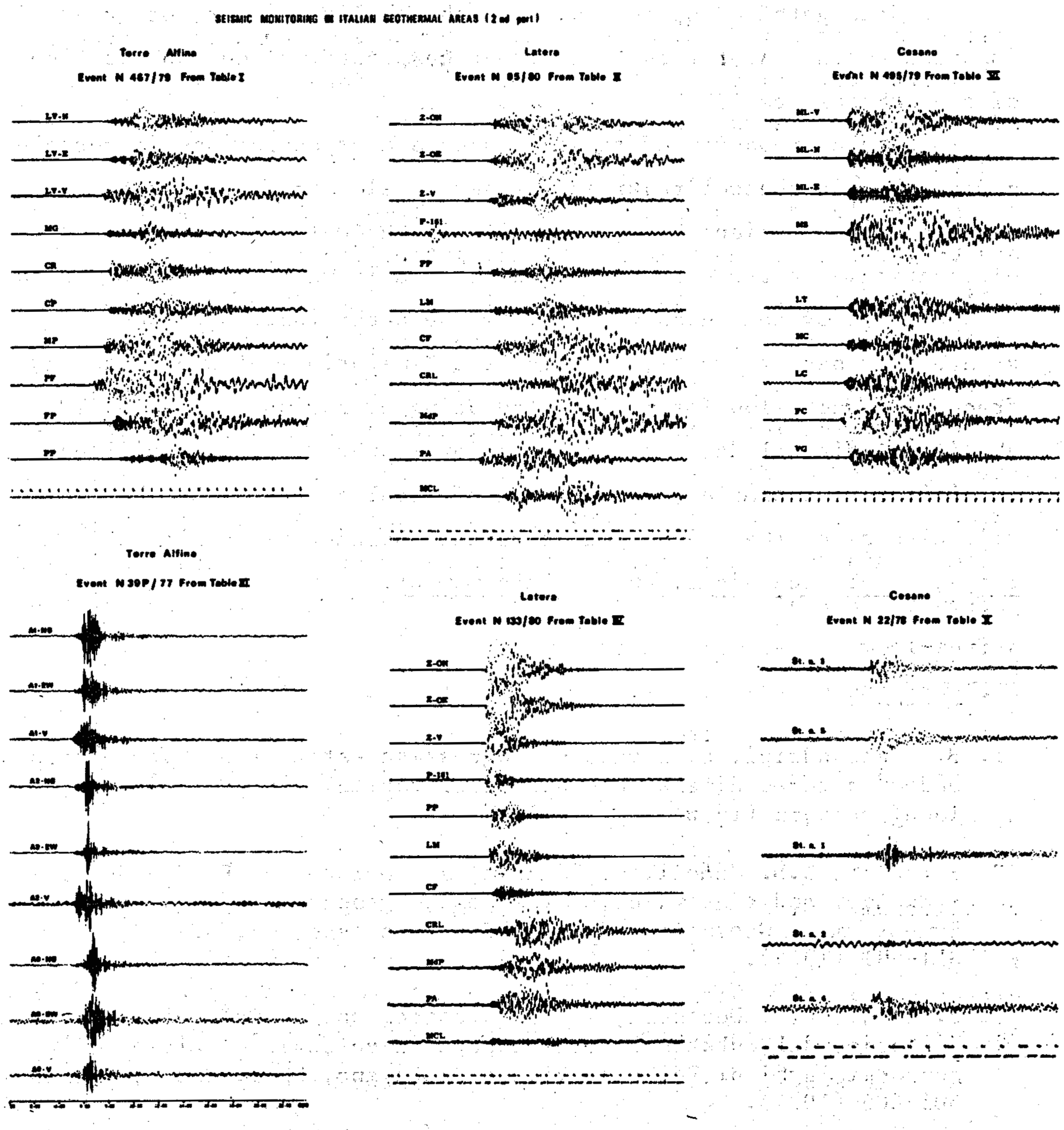

Plate 6. Seismograms of a few events in all three areas.

The data gathered up to now, even though limited, are of great importance since it refers to a situation preceding the exploitation of a geothermic camp.

In future expansion of this research and of operations in certain camps, seismic control requires further development in order to achieve more efficiency in data-collecting as well as in methods of elaboration. Instruments with greater dynamic range are needed, such as a digital system which would allow the determination of the greatest number of events, reducing the limitations of amplitude and frequency, and allow for rapid calculating operations. The availability of digital data is necessary for elaboration which will not be limited to a simple determination of focal co-ordinates, but which will also allow the definition of certain parameters such as signal range, focal mechanisms, and seismic moment.

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