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Crustal model and local magnitude at El Cabril (Spain)

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ABSTRACT: The Microseismicity Survey of El Cabril has included the determination of a local crustal model. The records of explosions of several quarries and mines has been used to construct the travel-time curves, from which the thickness and P-velocities of superficial crustal layers have been derived. Furthermore, the formula of Richter's Local Magnitude has been applied, with attenuation curves specifically developed for this area of the Hercynian Massif in the Iberian Peninsula. In both cases, the results have been satisfactory.

1 INTRODUCTION

El Cabril is a facility for Low and Medium Level Radioactive Waste, operated by Enresa, Empresa Nacional de Residuos Radiactivos, S. A. It is located in the southern limit of the Hercynian Massif in the Iberian Peninsula. See figure 1.

A long microseismicity survey is being carried out by means of a network with 7 stations, one central, triaxial and six peripheral, vertical. The seismic signal from seismometers Mark L-4 is sent in analogic form via radio to the Registration Center where it is drawn on thermic paper.

The surface covered by the network is 40 x 50 Km, and the diameter of the area surveyed, 100 Km.

To improve the quality of the Microseismic Study it has been neccessary to construct a specific crustal model and to consider the various scales of magnitude. This has led to the completion of research outlined below.

2 CRUSTAL MODEL

Several models are been presented by different authors for the crust in the Hercynian Massif of the Iberian Peninsula. Figure 2 shows a summary of its principal features.

All the models define a similar thickness for the crust (slightly over 30 Km). As a first approximation they can be simplified in two layers. The first one has a thickness of 15-17 Km and a P-velocity of 5.6-5.7 Km/s. The second one has a thickness of 15-20 Km and a P-velocity of 6.6-6.7 Km/s. However, the differences in detail are important; this is partly due to the fact that they come from different zones. Concretely, the upper layer described in some models with P-velocity of 3.3-4.5 Km/s is only applicable in areas of thick mesozoic-tertiary sediments, not found in El Cabril Area.

There are numerous important quarries and mines around El Cabril. There has also been a large excavation in rock to build the radioactive waste repository. Figure 1 shows the location of these places. All their explosions are systematically recorded in the microseismicity network. Several explosions from each site have been utilised to study the crustal model. Arrivals of P-waves are easily identified on the analogic records, but a systematic reading of the S-waves arrivals has not been possible. So, only the model for the P-velocities has been established.

The origin time for the explosions is unknown. Hence, it is not possible to draw a normal travel-time curve. The procedure to compute the P-velocity has been the following:

a) Compute metric distance L_i between each explosion and each station using UTM coordinates.

b) Read the time PT_i of arrival of P-wave to each station.

c) Compute the difference of the arrival time to each station minus the arrival time to the first station $DT_i = (PT_i - PT_1)$.

d) Plot of points DT_i versus L_i (figure 3).

For each quarry or mine, the points (L, DT), representing the P arrivals to the different stations, are well fitted by a straigth line, indicating a P-velocity constant in the corresponding range of distances. The table 1 include the resultant values.

P-velocity values can be grouped into three sections:

a) The explosions from El Cabril, registered in the network at distances of 2.3 to 27 Km indicate a v_p=5.6 Km/s.

b) The explosions from the quarries Castillo, Massur and Parroso, registered in the network at distances of 14 to 72 Km indicate a v_p=5.5 Km/s.

c) The explosions from the mines of Aznalcollar and Puertollano, registered in the network at distances of 74 to 149 Km indicate a v_p=6.2 Km/s.

These results could concord with a continuous growth of v_p with the depth. Nevertheless, a model in echelon has been preferred, because it is more usual in the computer codes to locate the microseisms. To define it, the travel-time curve of figure 4 has been formed.

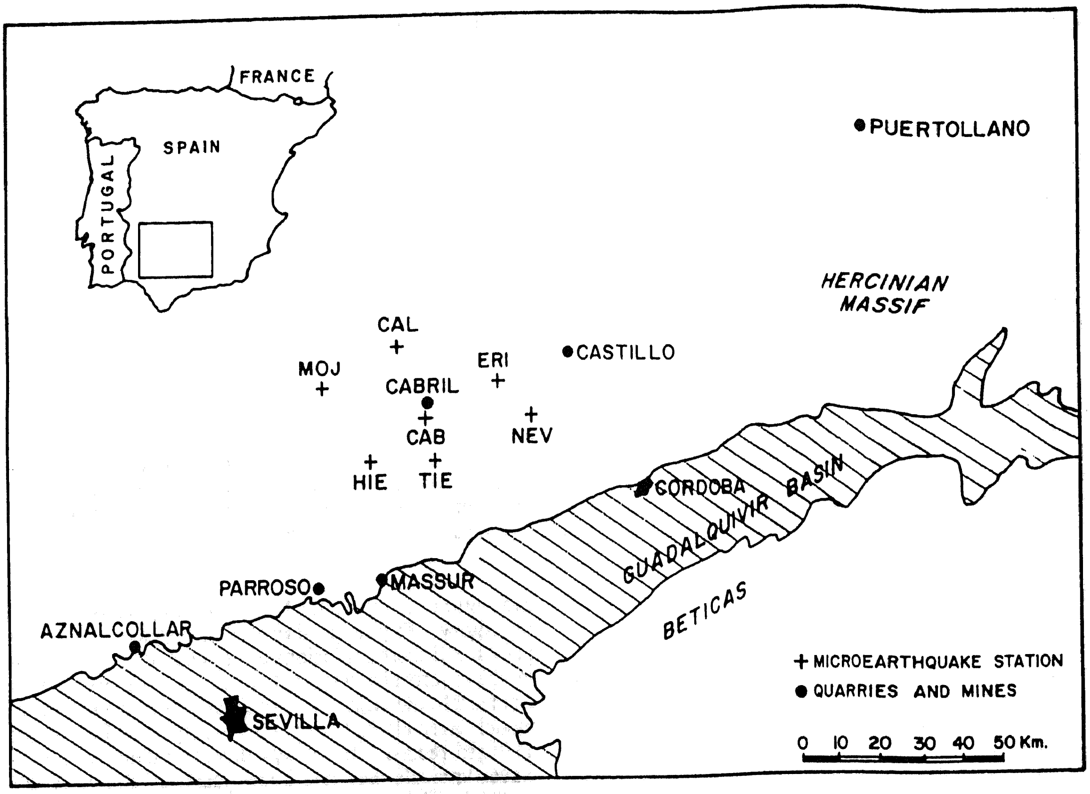

Figure 1. Situation of the studied area.

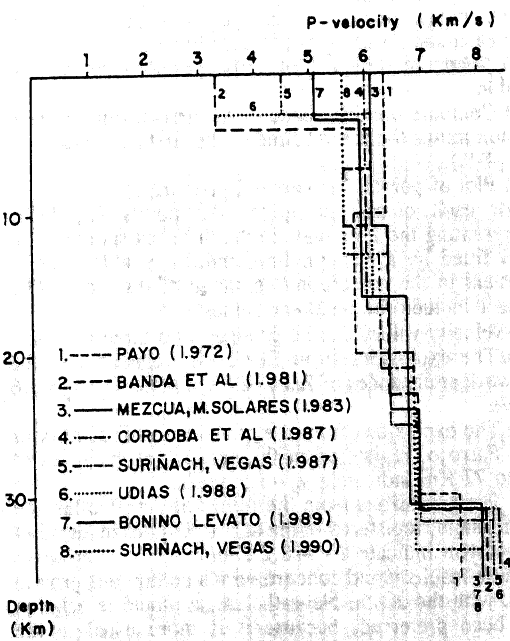

Figure 2. Previous crustal models.

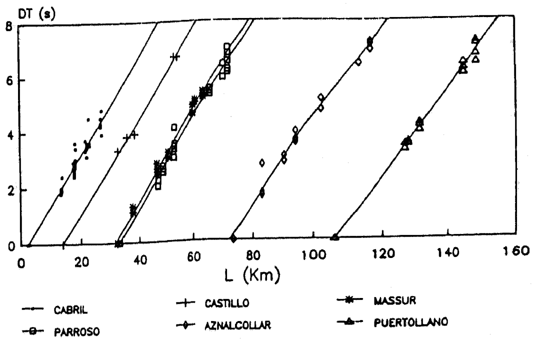

Figure 3. Relative arrival time versus distance.

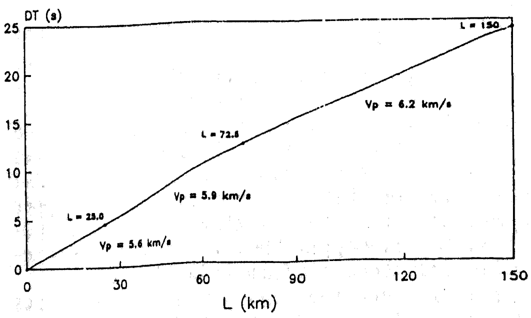

Figure 4. Composed travel-time curves.

Table 1. Range of distances and P-velocities for each quarry or mine.

	Cabril	Castillo	Massur	Parroso	Aznalcollar	Puertollano
No. of Points	56	6	19	30	18	22
L_{min} (Km)	2.3	14.0	32.3	33.1	73.6	106.2
$L_{máx}$ (Km)	27.2	54.0	63.3	71.7	116.2	149.0
v_p (Km/s)	5.60	5.91	5.89	5.95	6.17	6.25
Correlation coeficient	0.985	0.998	0.997	0.994	0.993	0.998

The P-velocities and critical distances are indicated in table 2. The thickness of the first crustal layers (also outlined in table 2) have been derived with the usual formulations of geophysical prospection.

Table 2. Basic P-velocities, distances and depth of layers

Layer	P-velocity (Km/s)	Distance (Km)	Depth (Km)
1	5.6	0-25	0-2.0
2	5.9	25-72.5	2.0-8.2
3	6.2	72.5-≥150	8.2-≥13.9

For deeper layers it is not possible to get the P-velocities with the data supplied by this quarries and mines. However, the difference between the several previous models is not important. Finally, the lower part of the crustal model for the Microseismicity Survey of El Cabril has been structured the same as the Bonino-Levato model, because of its general reliability and the relative concordance with the specific determination for the upper layers. Thus the crustal model presented in table 3 has been adopted:

Table 3. Crustal model adopted in the Study of Microseismicity at El Cabril

Layer	Depth (Km)	P-velocity (Km/s)
1	0-2.0	5.6
2	2.0-8.2	5.9
3	8.2-16	6.2
4	16-30.7	6.7
5	>30.7	8.0

3 MAGNITUDE SCALE

In numerous microseismicity studies, the scale of Magnitude-Duration is preferred to the Local Magnitude. In the Study of Microseismicity at El Cabril both scales are been utilised.

3.1 *Magnitude-Duration*

The scale of magnitude in function of the duration has been determined by an adjustment with the magnitude values assigned by other networks (IGN and RSA) to some regional events. The utilization of the results in the microearthquakes near El Cabril require a double extrapolation: (a) The control events come from areas relatively far from the El Cabril network, faced with the short distances (generally less than 50 km) of the microearthquakes of interest, and (b) they have magnitudes greater than the latter. The correlation finally adopted has been:

$$M_t = 1.96 \log t + 0.0029 D - 1.79 \qquad (1)$$

where t is the duration in seconds and D the epicentral distance in kilometers.

3.2 *Local Magnitude*

The Local Magnitude has been used, adapting the Richter(1958) scale to the El Cabril conditions.

Not been able to count on Wood-Anderson (WA) seismometers, it has been necessary to convert the recorded displacements to ground movements and then to Wood-Anderson amplitudes, through the expression:

$$A_{WA} = \frac{A}{M(T)} 2800 \qquad (2)$$

where A is the amplitude in mm read in the record, M(T) is the recorder magnification according to its corresponding calibration curve and 2800 is the amplification of the Wood-Anderson seismometer (constant in all the range of frecuencies of interest).

The error which can be made in this process depends on the precision in the measurement of the period for the maximun amplitudes of the record and on the form of the magnification curves of the local network. In the case of El Cabril, for the periods of 0.1 to 0.5 s, an error of 0.1 s in the estimated period can, in the sum, produce an error in the computed magnitude of 0.1-0.2 units.

In agreement with the Richter formulation, the Local Magnitude will be:

$$M_L = \log A_{WA} - \log A_0 = \log\left(\frac{2800A}{M(T)}\right) - \log A_0 \qquad (3)$$

The term $-\log A_0$ represents the distance normalization. It was established by Richter for California and for earthquakes with an average focal depth of 16 km. In order to apply it in El Cabril two factors have been necessary to evaluate: (a) Difference of inelastic attenuation between California and the Hercynian Massif of the Iberian Peninsula and (b) Difference of attenuation of earthquakes more superficial than 16 km.

The difference of attenuation between California and the Iberian Hercynian Massif has been estimated, assuming that the phase of maximum amplitudes is formed, in both cases, by waves Lg of no-Airy type. Its amplitude depends on the distance according to the expression (Nuttli, 1973):

$$X = X_0 R^{-1/2} (\text{sen } R)^{-1/2} \exp(-\gamma R) \quad (4)$$

The difference between the terms $-\log A_0$ of California and of the Iberian Hercynian Massif would be:

$$\delta(-\log A_0) = -\log A_0(\text{Ib}) + \log A_0(\text{Cal}) = \frac{(\gamma_{Ib} - \gamma_{Cal})R}{\text{Ln}10} \quad (5)$$

Nuttli (1973) indicates that a coefficient $\gamma=0.0054$ Km^{-1}, corresponding to a value Q=275, adjusts to the terms $-\log A_0$ given by Richter (1958), for an average frequency of 1.7 Hz. On the Iberian Hercynian Massif a value Q=625 could be adopted (Romacho, 1988).

Table 4 shows the differences in the terms of attenuation between California and the Iberian Hercynian Massif, including Q_{Ib} notably higher than expected. In all cases a S-velocity of 3600 m/s has been considered. As can be observed, The difference in the term $-\log A_0$, in the range of distances of interest, is less than about 0.1 magnitude units.

Table 4. Factors of correction of the Richter's Local Magnitude term of attenuation for local values of Q.

Epicentral Distance (km)	$\delta(-\log A_0)$		
	Q=500	Q=1000	Q=5000
10	0.01	0.02	0.02
20	0.02	0.03	0.04
30	0.03	0.05	0.07
40	0.04	0.07	0.09
50	0.05	0.08	0.11
100	0.11	0.17	0.22

The difference of attenuation in earthquakes more superficial than 16 km has been calculated with a procedure similar to that of Brune and Allen (1967). It has been supposed that for epicentral distances of more than 24 Km a correction for the focal depth is not required. For smaller distances it has been assumed that: (a) In events of depth >= 16 km the term $-\log A_0$ is the same as Richter's and (b) in events with focal depth = 0 km the attenuation is equal to that of the explosions in the zone. This has been determined by selecting seven explosions (325 to 2550 kg of explosives, Magnitude-Duration = 1.3 to 2.0) from El Cabril excavations. Their amplitudes and predominant periods has been read in the recordings of each station and the equivalent Wood-Anderson amplitudes have been calculated, normalizing to coincide with the Richter's values at an epicentral distance of 24 Km. Figure 5 shows: (a) The curve of $-\log A_0$ after Richter (1958), (b) the average values of normalized explosion amplitudes at each station and (c)the curve that best fits these points. This curve defines the attenuation factors $-\log A_0$ for zero-depth events near El Cabril. At intermediate depths it is necessary to interpolate. Finally, table 5 contains the attenuation factors $-\log A_0$ used in the calculation of Local Magnitude including the corrections for inelastic attenuation and for focal depth.

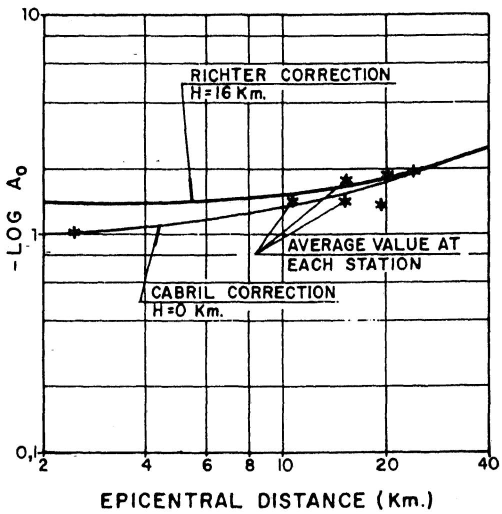

Figure 5. Richter and El Cabril attenuation curves to compute the Local Magnitude for events with epicentral distance smaller than 24 Km.

4 CONCLUSION

The structure of the more superficial crustal layers in the Hercynian Massif around El Cabril has been determined. With this objective, a composed travel-time curve has been drawn using the records of explosions in some quarries and mines in a circle of 130 km in radius centered in El Cabril. The distance from the explosion sources to the recording stations reached 150 km. The penetrations of the seismic waves generated by the explosions have not reached more than 15 km. With this data three layers have been distinguished, with thickness of 2.0, 6.2 and more than 5.7 and with P-velocities of 5.6, 5.9 and 6.2 km/s. The third layer has been extended to 16 km of depth, taking into account the crustal models published by other authors. Besides, a fourth one has been added down to a depth of 30.7 km, with P-velocity of 6.7 km/s.

Table 5. Values of $-\log A_0$ to calculate the Local Magnitude in the Microseismicity Survey of El Cabril

Epicentral Distance (km)	Focal depth (Km)		
	0	8	16
5	1.1	1.3	1.4
10	1.4	1.4	1.5
15	1.6	1.6	1.6
20	1.7	1.7	1.7
25	2.0	1.9	1.9
30	2.2	2.1	2.1
35	2.4	2.3	2.3
40	2.5	2.4	2.4
45	2.6	2.5	2.5
50	2.7	2.7	2.6
55	2.8	2.8	2.7
60	2.9	2.9	2.8
65	2.9	2.9	2.8
70	2.9	2.9	2.8
80	3.0	3.0	2.9
90	3.2	3.1	3.0
100	3.2	3.1	3.0

The scale of Richter's Local Magnitude has been adapted to be used with the data of the El Cabril microseismicity network. Two corrections have been made to the Richter $-\log A_0$ term: Firstly the difference in the inelastic attenuation between California and the Hercynian Massif of the Iberian Peninsula has been analysed, concluding that it has practically no influence on distances of less than 100 km. Secondly the values of the term $-\log A_0$ for focal depths of less than 16 km (considered by Richter as an average value of the Californian earthquakes) has been established. For this, the attenuation of explosions in the zone has been used, converting the recorded amplitudes to Wood-Anderson ones. Table 5 shows the values of the term $-\log A_0$ finally used in order to assign Local Magnitude to the microearthquakes around El Cabril.

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