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A SIMPLE METHOD OF QUANTIFYING THE DEPENDANCE OF THE DEPTH OF THE HYPOCENTER OF AN EARTHQUAKE UPON THE VELOCITY MODEL

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Abstract—The correct calculation of the depth of an earthquake is important, because incorrectly estimated depths can lead to wrong assumptions about the tectonic structure of the area in which the seismic event occurred.

This is especially important during the processing of microearthquake data, where a few incorrectly calculated depths can complicate the geological interpretation of the overall results.

This paper describes a simple method for testing the calculated depths of events obtained from microearthquake networks and applies it to some data from a microearthquake study of northwestern Greece.

Key Words: Hypocenter, Microearthquake, Velocity model.

INTRODUCTION

It is well known that the seismic events which occur within an area reflect its tectonic activity and that they can provide information about its geological structure. It also is clear that any seismic analyses are not likely to yield results that are reliable unless a thorough knowledge of the distribution of the depths is available first.

The accurate locations of earthquake events, becomes extremely critical during microearthquake surveys where a few incorrectly located events can complicate the geological interpretation of the overall results.

Investigations have suggested (Lee and Stewart, 1981) that if the crustal structure is homogeneous, stations in a seismic network should be distributed evenly by azimuth and distance. To obtain a reliable focal depth, the distance from the epicenter to the nearest station should be less than the focal depth. If earthquakes are distributed uniformly over a region of area A, then a network of approximately A/L^2 stations, where L is the station spacing, is required.

Optimal distributions of stations has been studied by many authors (Peters and Crosson, 1972; Lilwall and Francis, 1978; Uhrhammer, 1980).

After a microearthquake network is in operation, one of the first problems which the seismologists face (Lee and Stuart, 1981), is to determine the basic parameters of the recorded events, such as origin time, hypocentral location, magnitude, fault plane solutions, etc. This problem has been studied extensively in seismology and many location algorithms generally have been available (Crampin, 1970; Lee and Lahr, 1975; Lee and others, 1981).

All of the location algorithms which are in use today are based upon certain assumptions about the velocity structure (velocity model) of the area. The unknown cross section is replaced by a set of parameters and the determination of the cross section is reduced to the determination of numerical values of the parameters. Theoretical values are compared with real data and the discrepancy between the computed date and the observed ones is calculated. The set of cross sections for which this discrepancy is sufficiently small is the solution of the problem.

From the discussion, it is evident that in many situations the calculated depths of the seismic events might depend strongly upon cross section parameters. Thus, it is helpful to be able to test the validity of the obtained results before proceeding into their geotectonic implications. This becomes important when we are concerned with data from areas having a complex tectonic structure, whose velocity model is little known.

It is the purpose of this paper to describe to a simple technique for testing the dependence of the hypocenter of microearthquakes upon variations of the assumed velocity model.

OUTLINE OF THE METHOD

Consider an area A, and let $S_1, S_2, \ldots, S_k$ be a seismographic network located within the area. Let $E_1, E_2, \ldots E_N$ be the seismic events which occurred within a time period T.

A routine seismological investigation consists of using the seismic wave arrivals at the seismograph stations and of locating the seismic events with a location program. Usually during this process, a velocity model is assumed and its parameters are adjusted accordingly in order to minimize some functional RMS.

Let $\mathscr{L}$ be the class of all the earthquakes occurred within the area and let $\bar{z}$ be their mean depth of occurrence. We say that an isolated seismic event E_j belongs in class $\mathscr{L}$ if its depth z_j is within a certain limit a% of the mean depth $\bar{z}$:

$$E_j \in \mathscr{L} \longleftrightarrow z_j \in (\bar{z} - a \times \bar{z}/100, \quad \bar{z} + a \times \bar{z}/100). \qquad (1)$$

It is evident that from all the seismic events which occurred in the area A during the time period T, those that do not belong in class $\mathscr{L}$ possess the greatest probability of being located incorrectly. A geological meaning of this is that as experience shows, in a tectonically active area, most of the earthquakes occur within some characteristic depth limits, although this is not general. For example, there are situations characterized by a bimodal distribution of earthquake foci, with the smaller events closer to the surface. In such a situation two different classes $\mathscr{L}_1$ and $\mathscr{L}_2$ should be considered.

If the calculated depths for some of the located events do not permit to include them within class $\mathscr{L}$, a simple way to check if this is due to the effect of the strong dependance of the location procedure upon the velocity model, is to perform the following test.

We carry out the test using one-half space models, which give slightly poorer locations than using a layered model, but speed up the calculations and simplify the interpretation stage.

We begin by assuming a certain V_p/V_s ratio (V_p is the velocity of the P-waves and V_s is the velocity of the S-waves), and recalculate z_i for different P-wave velocities which cover the possible velocity variations in the area. This allows us to examine in a simple way how absurdly high or low P-wave velocities or extreme V_p/V_s ratios influence the calculated depths.

Let V_{pmi} be the P-wave (one-half space) velocity which gives the less RMS, and let z_{mi} the corresponding depth.

During the second stage of the test, a constant one-half space velocity V_{pmi} is adopted and the event is located at various fixed depths and for various V_p/V_s ratios.

If $z_{mi}(V_p/V_s)$ is the depth that gave the smallest RMS for the different values V_p/V_s used, we construct a parameter Q defined by the equation:

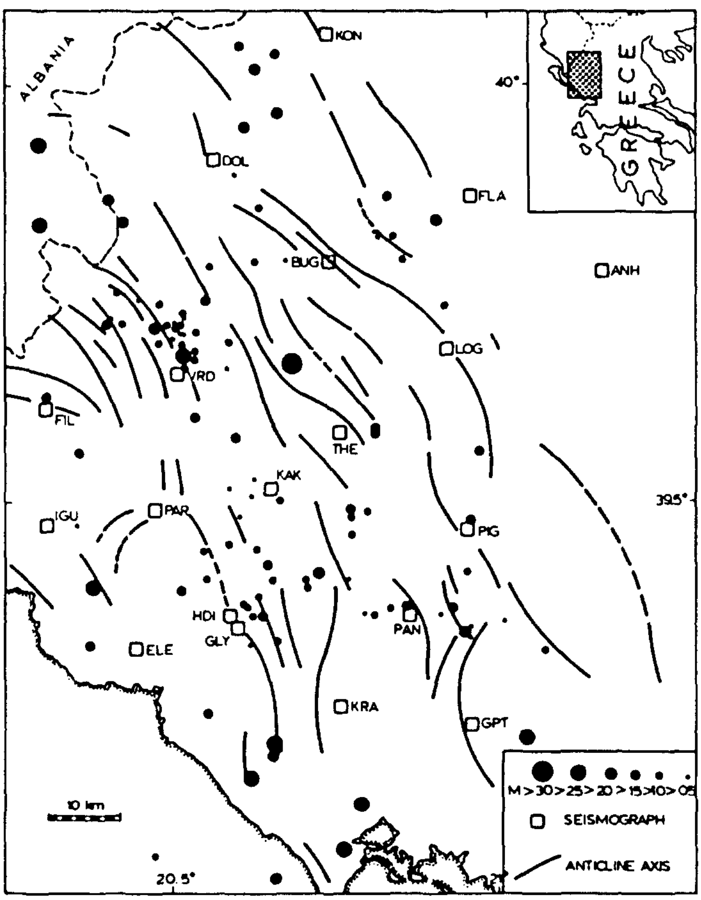

Figure 1. Map showing location of seismograph stations and epicenters of 148 events located using this array (solid circles).

$$Q = \left[z_1 - \frac{(z_{m1} + z_{m1}(V_{p1}/V_{s1}) + \ldots + z_{m1}(V_{pk}/V_{sk}))}{k + 1} \right] \times 100/z_1.$$

Obviously, if Q is within a certain limit %, of the originally calculated depth z_1, then the calculated depth for the specific event does not depend strongly upon the velocity model and can be accepted.

The authors have determined from experience that, using 3 velocity ratios V_p/V_s and considering a limit of 50%, satisfactory results are obtained. Of course, the specific values of the velocity ratios which have to be adopted during the calculations depend upon the general geological structure of the area under study and have to be selected carefully.

EXAMPLE

This section applies the given outlined procedure to data from a microearthquake study of northwestern Greece.

During 6 weeks between July and September 1979, 18 Sprengnether MEQ-800 portable seismographs were installed and operated in northwestern Greece (Fig. 1). The purpose of the microearthquake project was to understand the tectonic character of the area (King and others, 1983).

Some 250 events with magnitudes between about 0 and 3 were recorded during a 4-week period in which the whole array was installed fully and was functioning well.

The records were read using a lens and graticule with an estimated accuracy of 0.1 sec for P-waves and 0.3 sec for S-waves. Typical residuals calculated during the location process were of the order of 0.5 sec, so reading errors are not considered to be significant.

From the 250 events that occurred, 167 events were picked because they were recorded by at least five stations with at least one clear S-phase at one of the closest stations. After initial tests with one-half space models, using the HYPO71 location program (Lee and Lahr, 1979), these 167 events were located in 50 different two-layer structures. The depth of the interface was differed between 5 and 15 km and the velocities from 2.5 to 5.5 km/sec for the upper layer, and from 5 to 5.6 km/sec for the lower layer. The structure which gave the lowest RMS had a surface layer 10 km thick with a P-wave velocity of 5 km/sec overlying a one-half space with P-wave velocity of 5.8 km/sec.

Table 1. Calculated values of RMS for five different space velocities

Depth (km)			RMS			V_p
E_1	E_2	E_3	E_1	E_2	E_3	(km/sec)
20	20	20	1.23	1.21	1.09	4
23	22	21	0.40	0.21	0.12	5
25	24	22	0.20	0.04	0.06	6
28	27	23	0.23	0.22	0.23	7
30	30	22	0.39	0.30	0.54	8

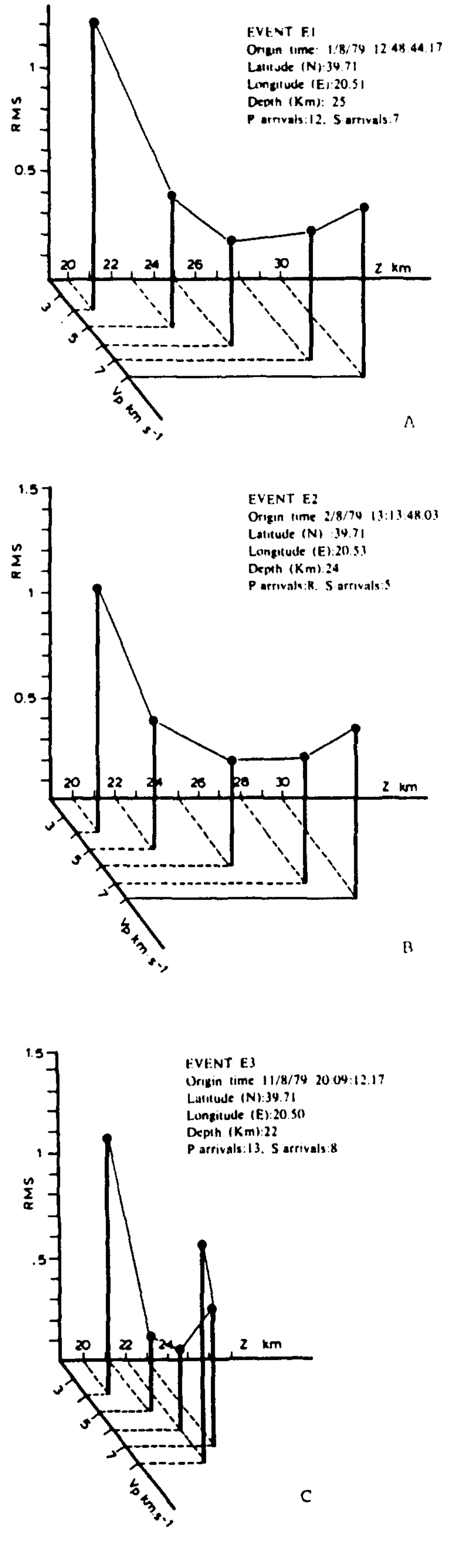

Figure 2. RMS residuals as function of one-half space velocity for three events. A V_p/V_s ratio of 1.8 was used.

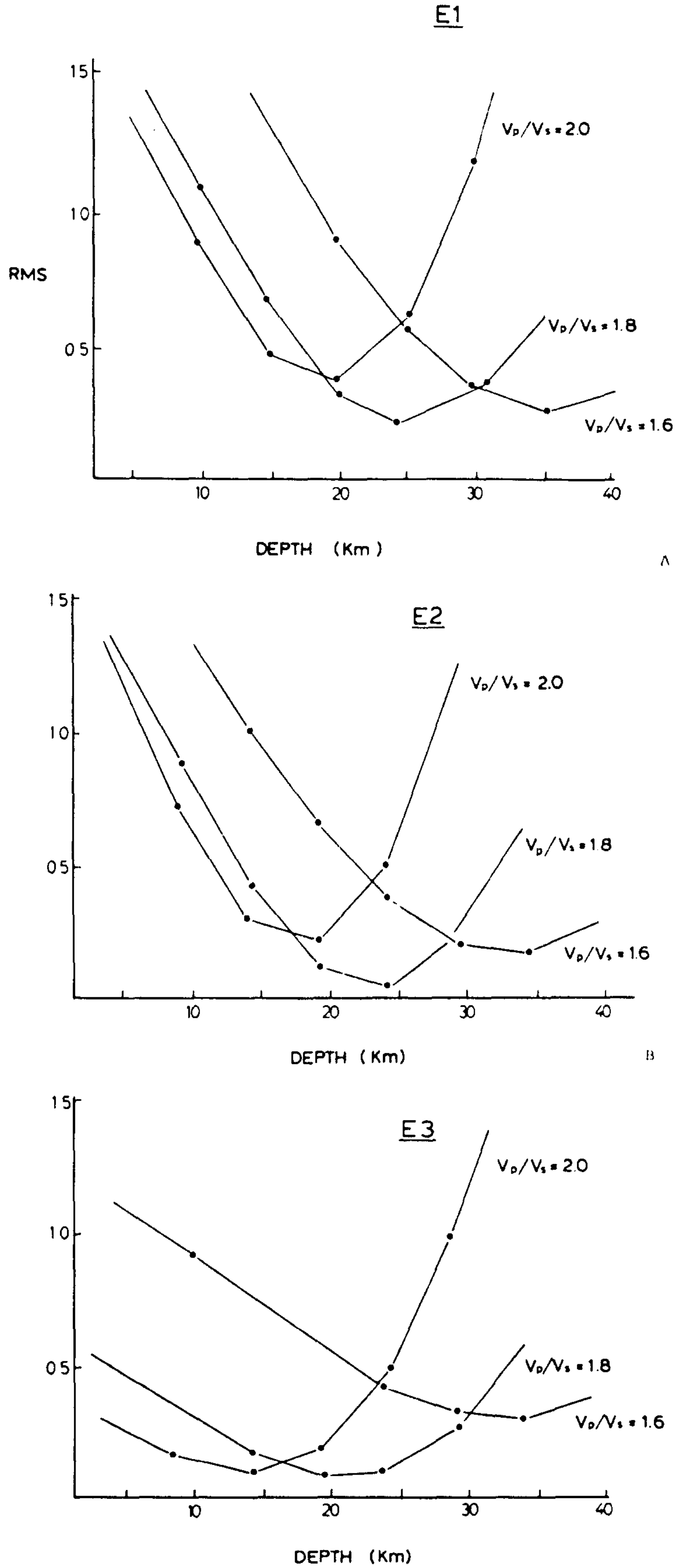

Figure 3. RMS as function of depth for three velocity ratios V_p/V_s = 1.6, 1.8, and 2.0. One-half space velocity of 6 km/sec was used.

Table 2. Calculated RMS at 8 fixed depths and for three different velocity ratios

Depth (km)	Earthquake E_1 RMS				Earthquake E_2 RMS				Earthquake E_3 RMS			
	V_p/V_s	1.6	1.8	2.0	V_p/V_s	1.6	1.8	2.0	V_p/V_s	1.6	1.8	2.0
5		–	1.52	1.31		–	1.37	1.22		1.09	0.47	0.22
10		1.75	1.09	0.88		1.4	0.88	0.68		0.97	0.30	0.12
15		1.30	0.62	0.49		1.0	0.40	0.29		0.72	0.17	0.08
20		0.90	0.30	0.39		0.64	0.10	0.19		0.57	0.07	0.15
25		0.59	0.20	0.62		0.38	0.02	0.50		0.40	0.08	0.48
30		0.34	0.30	1.19		0.20	0.22	1.24		0.30	0.22	1.02
35		0.25	0.62	2.18		0.15	0.68	2.40		0.28	0.56	1.73
40		0.31	–	–		0.25	–	–		0.39	–	–

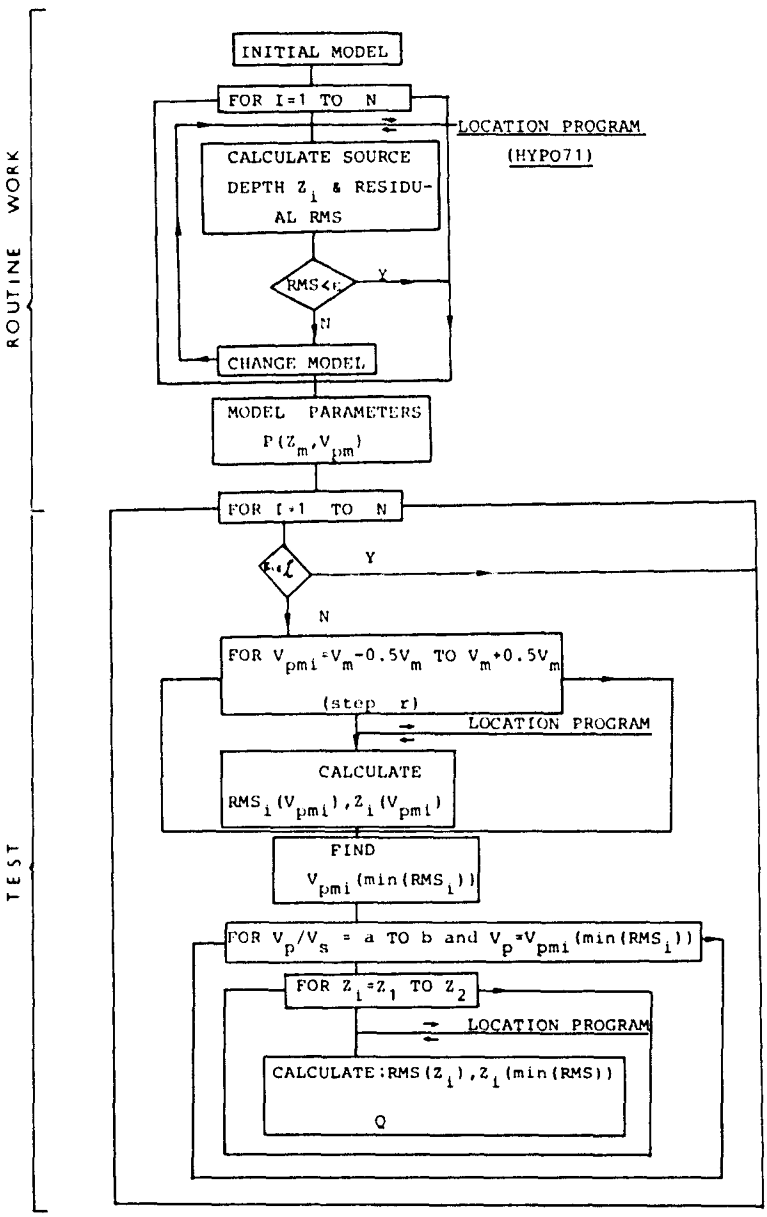

Figure 4. Block diagram of test.

A surprising result of the study was that some events seemed to have depths of 20 km or greater. To demonstrate that these depths were reliable the test outlined in the previous paragraph is applied to three well recorded events.

Following the procedure outlined previously, the events were relocated for various values of one-half space velocity and for $V_p/V_s = 1.8$. The results obtained are shown in Table 1 and plotted in Figure 2. As one can see from this figure, that even for extreme

Table 3. Earthquake depths z_i compared to test's depths and values of the calculated test's parameter Q

Earthquake	z_i (km)	z_{mi} (km)	$z_{mi}(1.6)$ (km)	$z_{mi}(1.8)$ (km)	$z_{mi}(2.0)$ (km)	Q (%)
E_1	25.1	25	35	25	20	5
E_2	24.1	24	35	25	20	8
E_3	21.9	22	35	20	15	5

values of P-wave velocities, none of the calculated depths is less than 20 km. The velocity value which gave the least RMS was 6 km/sec and this value was adopted for the second stage of the test, in which the events were relocated at fixed depths between 5 and 40 km and for velocity ratios V_p/V_s of 1.6, 1.8, and 2.0. Table 2 contains the obtained results and Figure 3 represents them in a graphic form.

As one can deduce from these graphs, for the high ratio of 2.0 the minimum in residual for only one event occured at 15 km, in any other situation the minimum occurred for depths > 20 km. Table 3 summarizes the test's results. Because the calculated Q-parameter is for all the situations < 10% (well below the upper limit 50%), we therefore can conclude that the calculated focal depths are real. A block diagram of the test is given in Figure 4.

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