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Small earthquakes observed with local seismometer networks

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Recent developments in instrumentation allow networks of radio-linked seismometers, recording on magnetic tape, to be easily established in areas of micro-earthquake activity. Observations with such networks enable the location and some of the source parameters of small earthquakes to be examined in detail.

Accurate locations require adequate knowledge of the velocity structure within the area of the network, and suitable source station geometry. Given such a network, it should be possible to estimate crustal structure sufficiently accurately to give good epicentre and depth locations for small earthquakes within the network.

1. Introduction

The relevance of micro-earthquake studies in a discussion of strain arises from the association of microtremors with regions of the Earth where the state of strain is changing. Strain may be released by processes, such as creep, which do not excite tremors, but all crustal earthquakes are associated with a more or less impulsive release of local strain.

Given sufficiently accurate focal locations, we can map the active areas, obtain evidence of the mechanism of deformation, and estimate the strain release from magnitude studies. In all these processes, the essential step is the determination of focal position, and, over the past few years, it has become possible to locate small earthquakes with much greater precision than before. This is due to the ease with which high-quality instrumental networks can now be established, together with the introduction of location programs, such as Eaton (1969), and the program FAMG described below, which use ray path travel times and are capable of treating complex structural models.

The determination of focal position with the necessary degree of precision requires knowledge of the velocity structure in the area, and arrivals with a good azimuthal distribution, covering a favourable range of distances from each event. Simple least-squares procedures can be applied to the more extensive sets of data, but there is a progressive loss of stability when the data sets become less complete. In the least favourable circumstances, one is reduced to the choice of the best-fitting member from an array of trial solutions.

2. Recording equipment

(*a*) *The I.G.S./Racal-Thermionic T*8100 *system*

The T8100 system was developed by Messrs Racal-Thermionic and the I.G.S. from the original portable tape-recording system of the University of Edinburgh, and is suitable either for the establishment of local networks, or for setting up teleseismic arrays.

The recorder writes 24 tracks of frequency modulated data on 1 inch (2.5 cm) tape giving 48 h of recording on a 20 cm diameter reel, accommodating seismic frequencies up to 20 Hz. The power consumption at the recording station is 15 to 20 W, including the operation of the timing system.

The seismometers at present in use are the 'Willmore mark II' instruments, which are normally set up with a free period of 1.0 s. The output is passed to amplifier modulators which emit a train of pulses at a rate dependent on the instantaneous level of the seismometer output. These amplifier modulators can receive power and deliver output through a single pair of conductors so that, when set up on cable links running to a recorder, all amplifiers can receive power from the recording point.

The f.m. signal can also be transmitted by u.h.f. radio; ranges up to 150 km being obtained between Yagi antennae with the radiated power of about 0.1 W. As the radio transmitters and receivers should be situated on high points of terrain to obtain maximum range, whereas the siting of seismometers and recorders may be dictated by different considerations, hybrid connexions using land lines from amplifier modulators to radio transmitters and from radio receivers to recorder are sometimes used. The output circuit of the radio receiver has an interface identical with that of the amplifier modulator, so that receiver power can be drawn from the recorder and only audio frequency information passed along the cable.

Playback is normally at 60 times the original recording speed and variable frequency filters may be used to improve the final output quality. Simple correlators are also used to assist the discrimination between P and S waves.

(*b*) *The new T*8050 *system*

A new system is now under development to meet requirements for field operations in the U.K. and overseas, making use of the latest advances of tape technology to improve portability, economy of power, and economy of magnetic tape. In the new system the packing density has been raised to the 'double' I.R.I.G. standard giving 28 tracks from a pair of interleaved 14 track heads on 1 inch tape. Longitudinal packing density has been improved to yield $3\frac{1}{2}$ days recording on a single pass of the tape with data frequencies up to 32 Hz, increasing to 14-day recording if the band width is reduced to 8 Hz. The mechanical system has been made symmetrical with automatic reversal, to permit the running time to be further extended by shuttling the tape and switching input from one set of tracks to another. The power consumption of the recorder and time encoder has been cut to about 3 W and the weight to about 15 kg. As a companion to this system, a new seismometer is under development having about one-quarter of the suspended mass of the Willmore Mark II while obtaining superior shielding by the use of a double-ended centre core magnet in a steel case. The design will also make it easier to install displacement sensors for long-period operation or tilt recording, and it is hoped that the overall mechanical stability will be sufficiently superior to that of the Mark II to enable such utilization to be comparable with that obtained from specialized long-period seismometers and tilt meters.

3. DETERMINATION OF FOCAL POSITION

The suite of near-earthquake location routines (FAMG), currently used by the I.G.S., calculates epicentre, focal depth, and magnitude of earthquakes observed with local networks, and extends that developed by Crampin (1970). Travel-times through a specified model are calculated for each iteration, using head waves for refracted phases, and direct paths for near stations. In principle, this method enables models of considerable complexity to be used, and, in particular, time terms are easily inserted into stratified models. The solution is found by successive iterations on a trial solution, seeking to minimize the root mean square residual. The solution converges sufficiently strongly for the arrival time and location of the nearest station to be used as the trial solution.

The factor which tends to generate instability when conventional least-squares procedure is applied is that the normal equations for latitude (ϕ), longitude (λ) and depth z involve the coefficients $\mathrm{d}t/\mathrm{d}\phi$, $\mathrm{d}t/\mathrm{d}\lambda$ and $\mathrm{d}t/\mathrm{d}z$, where t is the travel time of seismic waves along any given ray path.

When the focal position is changed, the order of arrival of the crustal phases may change at one or more of the stations in the network, thereby changing the identification of the first arrival. This will lead to discontinuous changes in the coefficients and in the residuals which make up the normal equations. The effect is much more serious in respect of variations of focal depth than

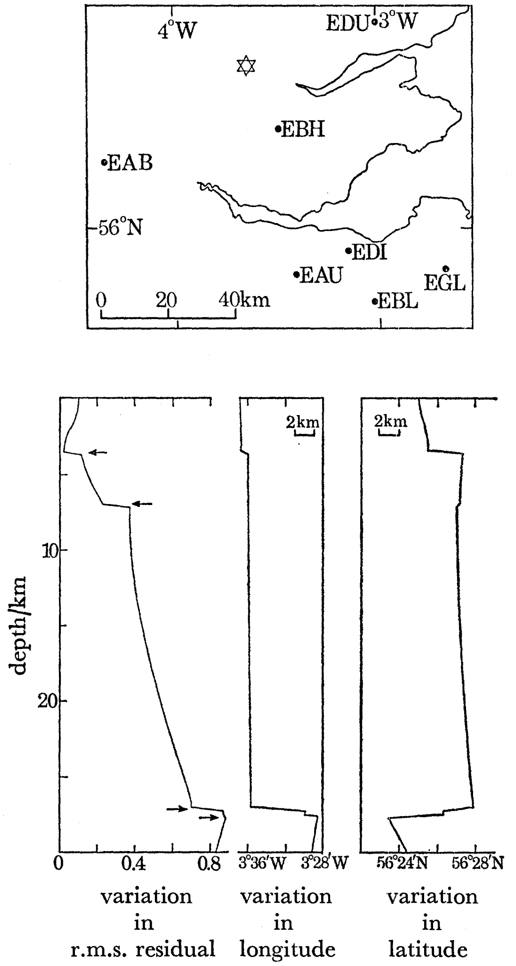

FIGURE 1. Variation with assumed depth of the r.m.s. residual, longitude and latitude in the determination of a small earthquake in Scotland (29 October 1970). The map shows the positions of the earthquake and the seven LOWNET stations. The arrows, on the variation of the r.m.s. residual, mark positions where the first arrival changes travel-time branch at one of the stations, as the assumed depth of the source changes.

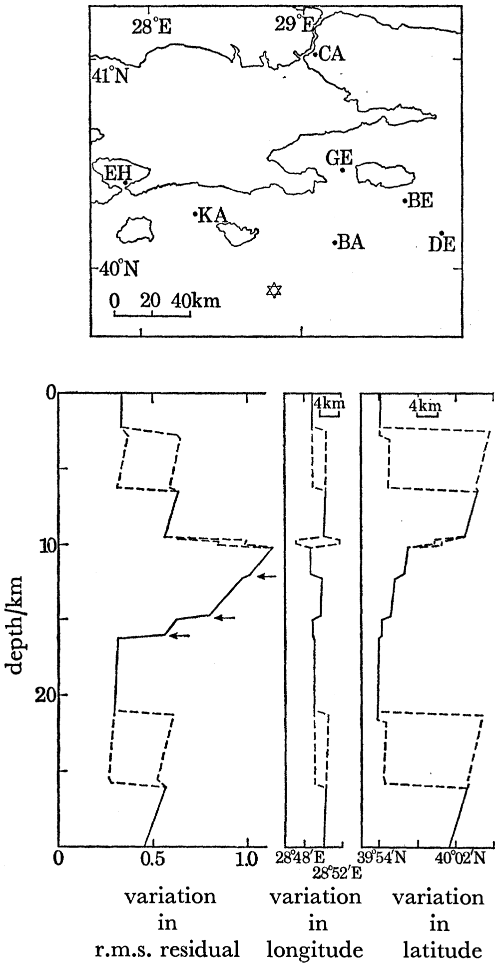

FIGURE 2. Variation with assumed depth of the r.m.s. residual, longitude and latitude in the determination of a small earthquake in Turkey (15 July 1971). The map shows the positions of the earthquake and the seven temporary stations of the 1971 Marmara Sea study. The arrows mark changes of travel-time branch at one station. The dotted lines show the range of the oscillating solutions for one computer run; different trial solutions will make the solution oscillate over a different range, but the oscillating property is fundamental to those positions.

it is for variations of the latitude and longitude in well-dispersed networks, so the technique, which is used in routine determinations, is to fix the depth at a succession of levels in the crust, to apply the ordinary least-squares procedure to the latitude and longitude at each depth, and to choose the solution which yields the smallest r.m.s. residual consistent with other features of the record.

Figure 1 shows the effect of applying the method to a set of readings obtained from an earthquake inside LOWNET (Crampin, Jacob, Miller & Neilson 1970). The discontinuities in the plot of r.m.s. residual against depth represent changes in phase identification appropriate to the assumed crustal paths for each depth, and the corresponding changes in latitude and longitude represent the effects of the resulting changes of coefficients in the normal equations. The solution is satisfactory, in so far as the r.m.s. residual shows a single clear minimum at the optimum depth, and independent evidence confirms the location to within 1 km in both epicentre and depth.

Figure 2 shows a less well-controlled solution, obtained for an earthquake on the southern fringe of a network recently deployed by the I.G.S. and Kandilli Observatory around the Sea of Marmara in Turkey. In this case, the uncertainties of propagation velocity within the crust lead to large residuals, and the network configuration causes the epicentral location to be highly sensitive to these residuals. In consequence, there are several ranges of depth in which the least-squares solution is unstable, and it seems as though nothing less than a point-by-point search through a three-dimensional array of focal positions will identify the best solution.

In most cases, it is found that, as in figures 1 and 2, the principal minimum of the r.m.s. residual lies at one extreme of the range of positions of the epicentre for different depths, which reinforces the importance of determining the correct focal depths in local epicentre studies. The number of discontinuities in the variation of the residuals with depth is a function of the geometry of the structure and the distances to the stations. The selection of the optimum network for the study of a particular source, which would minimize the number of discontinuities and reduce the chance of oscillation, requires a detailed knowledge of the crustal structure.

4. Determination of magnitude M_L

The current programme for the determination of magnitude utilizes amplitudes and periods from the seismograms which are converted via the known magnification curves to the equivalent deflexions of a 'standard' Wood Anderson instrument (Richter 1935).

The standard deviation of Richter local magnitudes calculated on a seven station network is usually less than 0.3, where stations with hypocentral distances less than 20 km have been omitted. Thus the sets of medium-range readings appear to be internally consistent, but there is doubt as to whether the general level of magnitude estimates bears the same relation to source energy as it does in Southern California.

5. Investigation of crustal structure from earthquake data

A further program (FASY) is under development, which uses the basic process of FAMG, and operates on a group of well-recorded events within a network, each having first arrivals from at least five stations. Models of the crustal structure are varied in a systematic way, and the structure selected which marks a minimum of the r.m.s. residuals summed over the group of events.

Extended networks of uniform station density are not very effective as a data source for this process. If there are no constraints on either structure or locations, the two are not independent, and the number of equations is unlikely to be sufficient to control the parameters.

It would appear that much better results would be obtained by the simultaneous deployment of two networks in a given area. One of these would have the maximum possible aperture in order to give paths with long segments at any refractor velocity, and would remain fixed in position for the whole of the field operation. The other network would have a much smaller aperture, and would move from one active part of the region to another, locating a few earthquakes within its coverage in each place. Focal positions and times of occurrence determined by the small network would then be used to establish the crustal model from observations of travel times by the larger network. The eventual accuracy of location throughout the region would then approximate to that obtainable from a network of density comparable to that of the small network extended over the entire area.

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