ROYAL NORWEGIAN COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH

PROCEEDINGS FROM THE
SEMINAR ON

SEISMOLOGY AND SEISMIC ARRAYS

OSLO, 22–25 NOVEMBER 1971

Editors: E S Husebye and H Bungum

Arranged in connection with the opening of The Norwegian Seismic Array (NORSAR) 1972

SOME POSSIBILITIES OF INTERPRETATION OF ARRAY STATIONS DATA

I.P. PASSECHNIK

Institute of Physics of the Earth
Academy of Sciences of the USSR
Moscow, USSR

INTRODUCTION

In the sixties array stations began to be used in seismology. At first these stations were intended to increase signal/noise ratio and to decrease the threshold of magnitude for detecting seismic events. However, it soon became apparent that array stations seemed to be powerful instruments for the detection and classification of seismic events, for studying the earth's structure as a whole and its separate parts (crust, mantle and core), for studying local structures in the regions where the stations are situated and for solving some other problems. A very good illustration of the above-mentioned is the recording of the early reflections of the phase P'P' by US array stations. These waves were reflected under Antarctica at discontinuities in the upper mantle at depths of 400 and 600 km (Adams, 1969, Engdahl and Flinn, 1969).

I should also like to point out the promising possibilities of studying small-scale horizontal inhomogeneities in the upper mantle structure by using array recorded short period seismic signals. Such a study is being carried out by Vinnik and Nikolaev (1969) in the USSR and Aki (1969) in the USA. This method may also be useful in the study of large scale horizontal inhomogeneities in the upper mantle by using the long period seismometer records of all the stations in the continent by considering such a network as a very large array.

The solution of such an important problem as the determination of the structure of the transition zone between the mantle and the core and the presence or absence of density jumps at this boundary might be possible only by studying PcP waves recorded in a zone near the epicenter. As it was shown in papers by Berzon et al, 1968, Berzon et al, 1972, and Kogan, 1972, the data observations of the ratio of PcP and P-wave periods, spectral and reflection coefficients for epicentral distances larger than 40° cannot be explained by a thick layer model for the core-mantle boundary. That is why a thin-layer model of the transition zone containing high velocity layers was developed. Examples of such models are illustrated in Fig 1.

The comparison of theoretical reflection coefficients (Fig 2) for a thin layer core boundary model with those calculated from observed data, taking into account the mantle absorption, shows that the coefficients are qualitatively in a satisfactory agreement. However, the solution of the problem of determining the parameters for a thin layer model of the transition zone would be possible by obtaining PcP wave records at small epicentral distances - lesser than 20° and in particular around 10°. Exactly in this zone information about PcP wave characteristics are available for developing transition zone models. Attempts to obtain recordings at epicentral distances smaller than 10° with a single seismometer have not been a success yet. Small-intensity PcP-waves in the above epicentral zone are likely to be obtained on array station records. It is obvious that the list of problems on the structure of the earth to be studied by array stations may be continued further.

A great deal of work has been devoted to the problem of seismic events classification from array stations records (Antonova, 1968, Passechnik, 1970, Anonymous, 1965, etc.). Their review is not my task. However, I should like to point out only that those excellent evaluations of capability of seismic event classification that were made in 1958-59 by the experts of the Geneva meetings, in official documents of UKAEA (Anonymous, 1965), in the memoranda of the Canadian and Swedish delegations at the Conference of the Eighteen-Nation Committee on Disarmament, Geneva (Anonymous, 1967), as well as in a report from the International Institute for Peace and Conflict Research (SIPRI) (Davis, 1968), are supported by today's experience. These

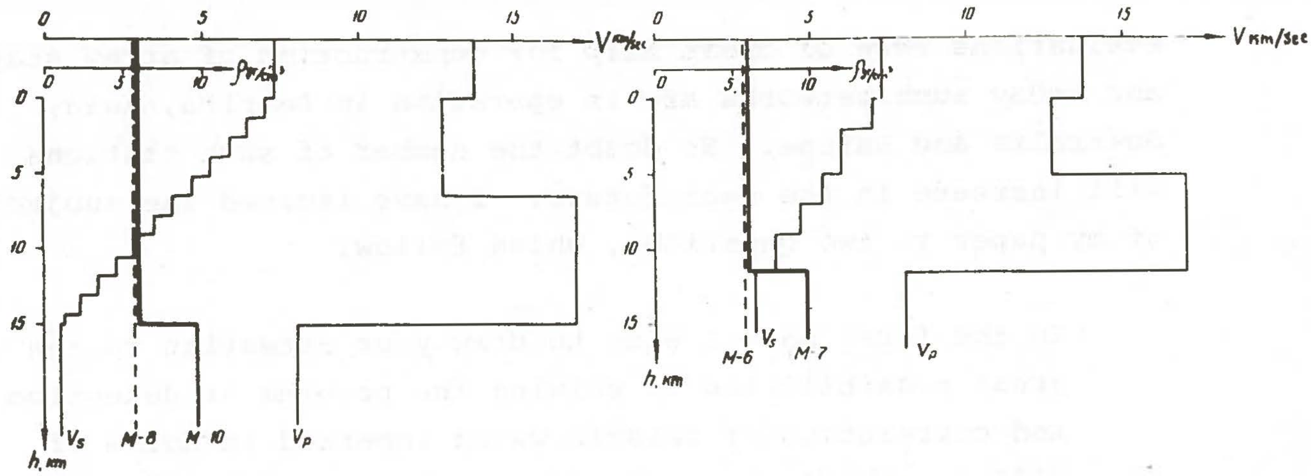

Fig 1. Examples of some models of the transition zone from the mantle to the core (M-7 and M-10 for ρ'/ρ = 1.7, M-6 and M-8 for ρ'/ρ = 1.0).

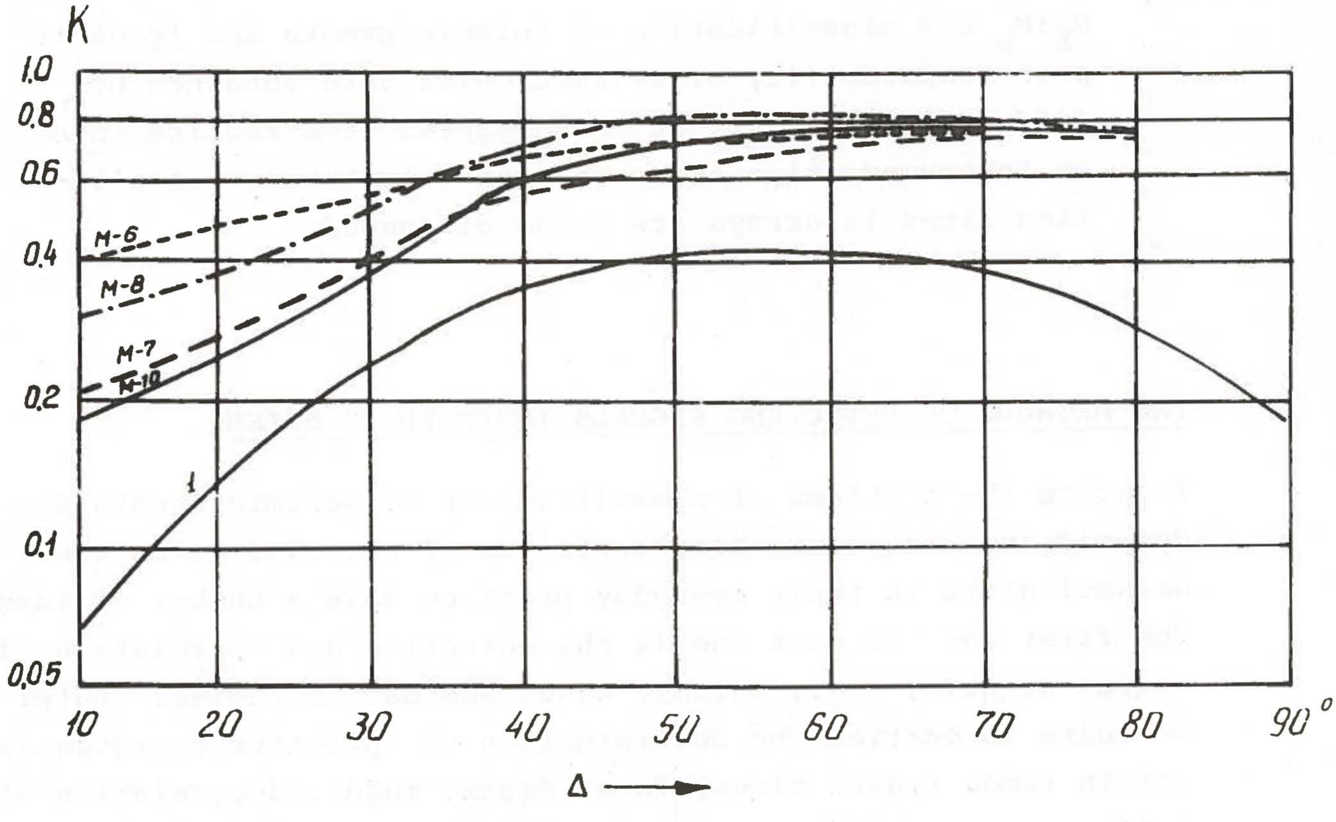

Fig 2. Theoretical curves of the reflection coefficients κ of PcP waves for the thin layered model of the transition zone from the mantle to the core (see Fig 1) and for the standard model (I): ρ'/ρ = 1.7; Vp = 13.7 km/sec; Vs = 7.25 km/sec; Vp = 8.0 km/sec; Vs = 0. Δ - epicentral distance in degrees.

evaluations were of great help for construction of array stations and today such networks are in operation in America, Asia, Australia and Europe. No doubt the number of such stations will increase in the near future. I have limited the subject of my paper to two questions, which follow.

In the first part I wish to draw your attention to the great possibilities of solving the problem of detection and correlation of seismic waves immersed in noise of different kinds by applying to seismic arrays the processing methods now being used in seismic prospecting. This part of the paper is a kind of a review.

The second part is devoted to problems concerning the significant differences in magnitudes M_b being determined using data of different stations and national networks. As it is well known, this makes it rather difficult to use the most effective magnitude criterion $M_S:M_b$ for classification of seismic events and leads to poor comparability of seismic event data obtained by different networks. In this respect some requirements on instrumentation and choice of seismometer installation sites in arrays are being discussed.

THE METHODS OF DETECTING SIGNALS IMMERSED IN NOISE

To solve the problems of classification of seismic events by dynamic and kinematic characteristics of recorded waves the seismologists in their everyday practice have a number of tasks. The first and the main one is the detection and correlation of useful signals, i.e., seismic waves admidst the noise. Later on there is carried out determination of epicenter coordinates, origin time, travel times, focal depth, magnitude, relation of different types of wave, intensities mainly under M_b and M_s magnitudes, spectral and polarization characteristics and some other parameters. Successful solution of all the latter tasks depends on the successful solution of the first main problem.

Seismic noise includes microseisms of different origin, regular waves from that source which generates useful signals, as well as from other seismic events. Depending on noise type, their spectral content, propagating velocity, degree of correlation with a useful signal, etc., several methods of detection and recording of seismic vibrations as well as different techniques of data processing are being used. Further, I shall briefly discuss the problem of detection and correlation of useful signals immersed in noise of regular character.

Today the event classification is being carried out by studying records of stations with one three-component set of seismometers, later on denoted 'single-channel systems', and by studying data from array stations, being called multi-channel systems. Naturally the capability of multi-channel systems is much greater than that of single-channel ones.

There are now very few multi-channel systems (about 10) and very many (more than 2000) single-channel systems. This is why classification is carried out with the help of single-channel stations. Single-channel systems are not able to detect any signals when signal/noise ratio is less than 1. With the help of such systems the problems of detecting the arrival of low intensity body and surface seismic waves immersed in nonstationary noise cannot be solved.

The nonstationary noise may be waves of other types connected with this phenomenon, for example, waves transformed at structural boundaries near the source or receiving point, monotypic multiple reflected waves from the boundary of the crust and Moho like pP and pS waves, or waves connected with earthquakes, etc. While interfering such noise with the useful seismic waves, their spectra overlapped with those of useful signals and autocorrelation functions may have similar forms, i.e., noise and signals may be nonstationary and nonstationary-connected, in space and time. Special experiments show that nonstationarity of the noise process in time may reach 30 per cent, in space 50 per cent, and nonstationarity of the connection of the process may be relatively 20 and 30 per cent. Signals and noise in cases under consideration turn out to be correlated and using optimum filtration in single-channel systems does not lead to a desirable and positive result. For the above reasons seismologists were forced to use array stations where it is possible to use decorrelational filters, channel summation and other methods for signal detection.

In creating array stations, experience gained in seismic prospecting based on simultaneous multi-channel (up to 60-100 channels) registration of seismic vibrations was used. In exploration work seismometer grouping has been used for more than 30 years already. Today practically all seismic prospecting work is carried out with the use of grouping, the simplest scheme of which, dating from the very birth of the method, represents simultaneous or with time-delays summing outputs of different seismometers. Switching of a group of several seismometers (10-60 and more) on one receiving channel is widely used. Some other methods are used too. Mobility is typical for seismic prospecting. Adaptation of instrumentation for quick moving of the seismometers to a new place with any desirable geometry allows one to use the most perfect methods for correlation of useful signals immersed in noise during recording as well as in the processing by modern computers. Seismic prospecting left seismology behind concerning level of development of getting seismic records and methods of their processing. This is natural, since seismic prospecting plays an important practical role and its development in all countries is given special attention and industries make great efforts and spend large amounts of money on it.

The largest accumulation of methods for seismic wave registration using group seismometers and processing the observed data by computers is accumulated in the reflected waves method - the main method of seismic prospecting. Hereby the greatest effect was obtained by combining some methods during registration of the vibrations (choosing of distances, shotpoint-seismometer, grouping geometry, using small subgroups, etc.) and corresponding methods of automatic processing of the data by analog and especially digital computers. Multi-channel systems observations allow use of methods of phased summation, i.e., summing with different time delays. This method makes it possible to carry out analysis of the wave field to correlate regular waves with different apparent velocities, being recorded in the same time interval. In cases when there are not any other regular waves in the recording interval of useful signal, phased summation improves its correlation by suppression of random noise. In cases when there are registered some other regular waves with apparent velocities V^x, differing from V^* of the useful signal, then useful signal detection is impossible by using only phased summation, especially when the interfering waves have large intensities. In such cases it is necessary to carry out subtraction of these regular waves, which we shall call coherent noise.

METHOD OF CONSECUTIVE SUBTRACTION OF COHERENT NOISE

This method is apparently being most widely used in the Soviet Union (Gurvifh et al, 1970, Melamud and Udin, 1967) and can be successfully used at existing array stations. Its mathematical foundation was given in papers by Nahamkin, 1966 (a), (b), 1967 (a), (b). The method is especially successful in cases when it is necessary to pick out from interfering vibrations separate waves differing significantly in apparent velocities. For this purpose, after phased summation they pass to consecutive subtractions of waves beginning with the most intensive ones. The wave being picked out by phased summation after normalizing the amplitudes is consecutively subtracted after introducing corresponding time delays from every trace of the initial seismogram.

Thus during this operation on the initial seismogram the most intensive coherent noise is suppressed. In case some other intensive noise waves are still present, the procedure described above is repeated. In such a way it is practically possible to pick out waves with amplitudes may time smaller than those of the coherent noise. Simultaneously with the subtraction of coherent noise, filtering of the vibrations and other operations are used as well. The described process is carried out either on analog devices or on digital computers.

I should like to illustrate this method by some examples. In Fig 3-5 you can see examples of applying the consecutive subtraction method to real seismograms, recorded by broad band instruments. Applying filters of different types to these records has not lead to identification of useful waves. But using the method of consecutive subtraction combined with simultaneous bandpass filtering gave positive results. For instance, in the seismogram (Fig 3a) after the first subtraction the most intensive wave with low apparent velocity was

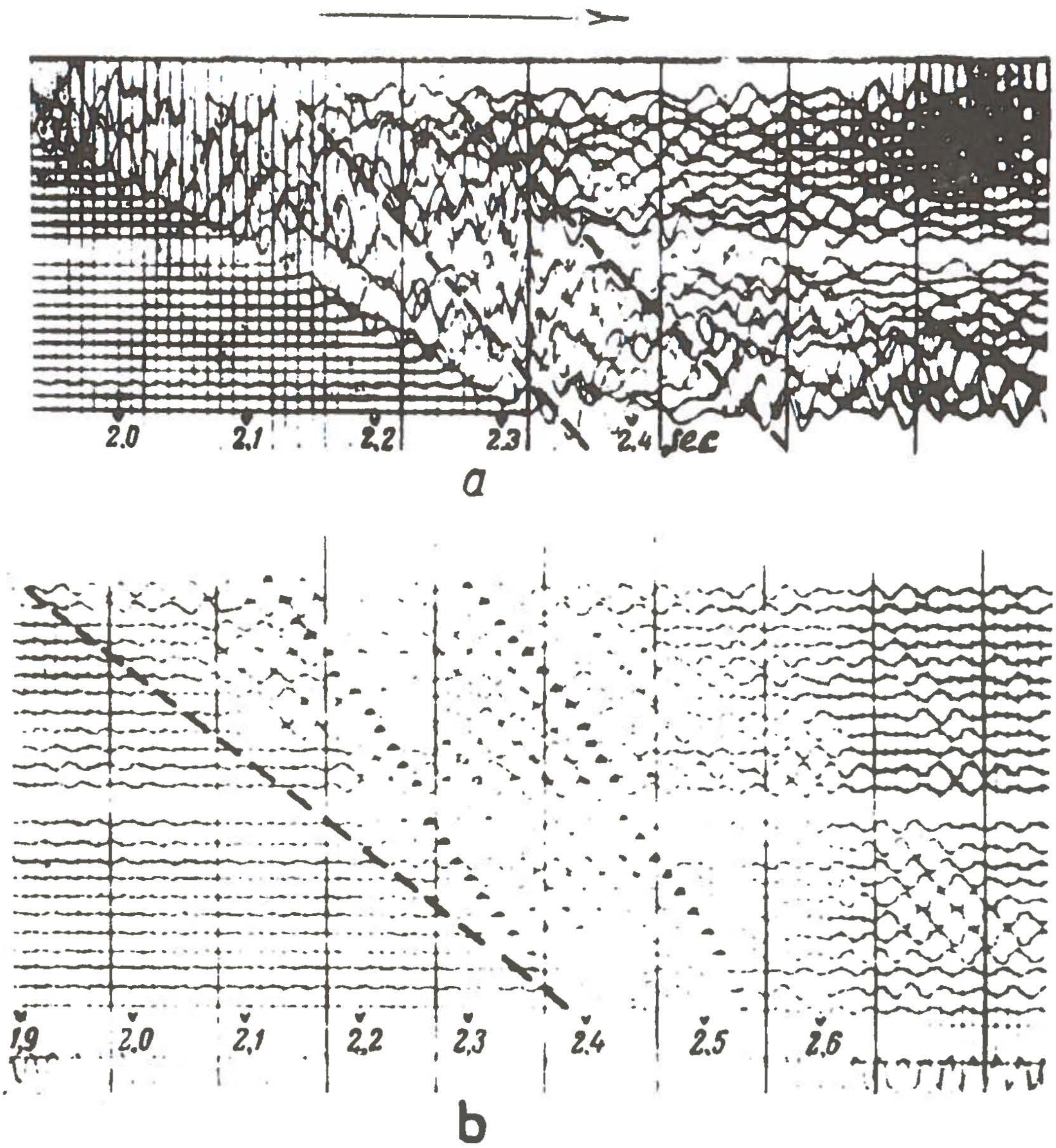

Fig 3. Seismograms illustrating the efficiency of the subtraction method
a) field seismogram obtained on the broad band apparatus
b) the same seismogram after the subtraction of the low-velocity waves.

excluded completely. Its arrival interval is shown in Fig 3b by dotted lines. Thanks to this we managed to pick out two more weak waves with large apparent velocities. In seismogram 3a the extrema of these waves are blackened.

In Fig 4 is an example of suppressing coherent noise. Fig 4a shows the original seismogram, while Fig 4b is obtained after subtraction and consecutive phased summation. It should be pointed out that it is impossible to pick out any regular waves on the initial record. Using the method of subtraction and phased summation, it is possible to pick out regular reflected waves from the original, irregular record.

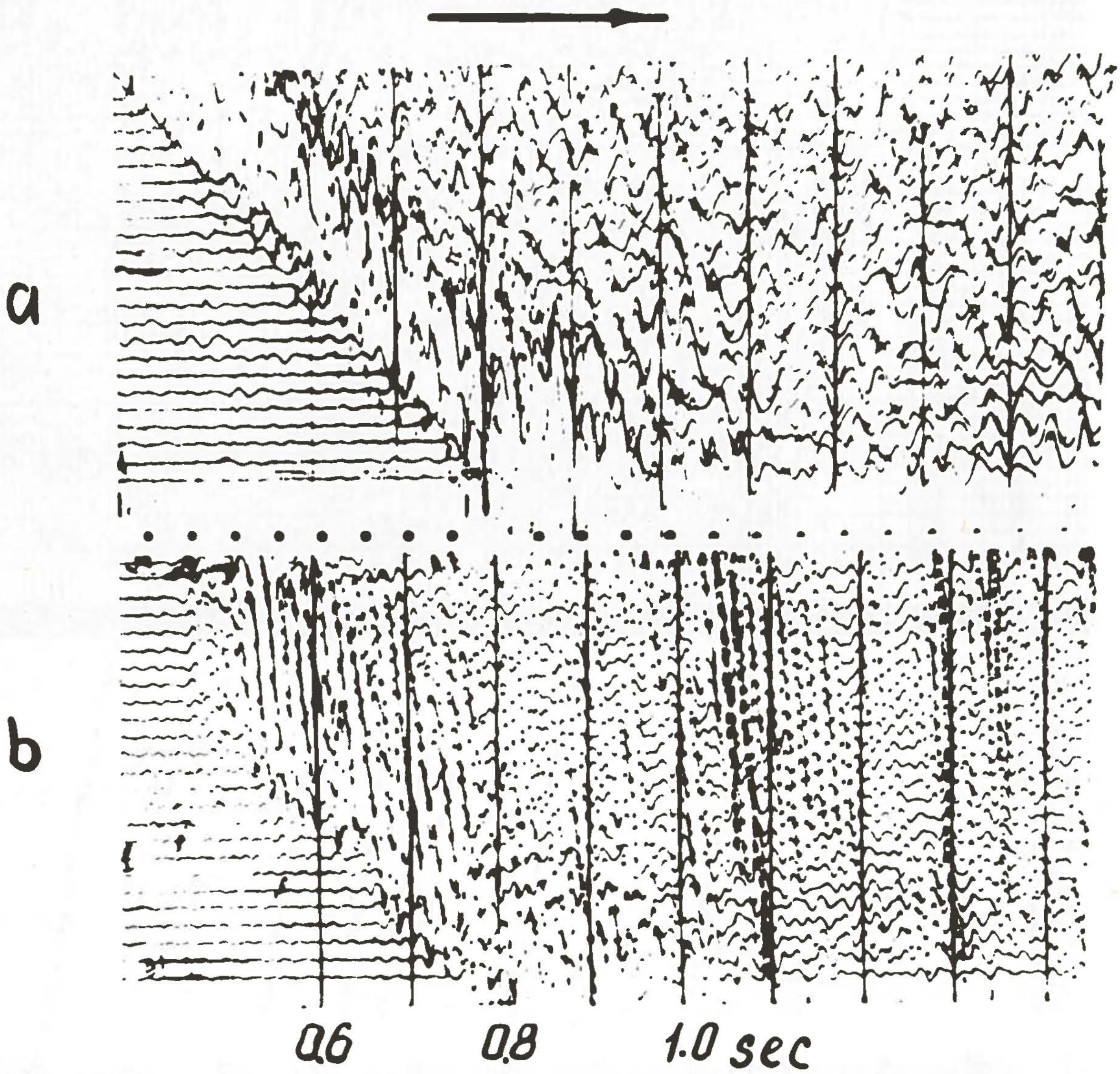

Fig 4. A seismogram similar to that in Fig 3.

A similar example is shown in Fig 5 at a vertical seismic profiling (Galperin, 1971). It concerns a case of observing waves in deep boreholes. In the initial seismogram (Fig 5a) incident and reflected waves are seen, incident waves interrupt correlation of reflected waves. After subtraction of the incident wave field and further phased summation, the reflected waves are strictly correlated at the whole vertical profile.

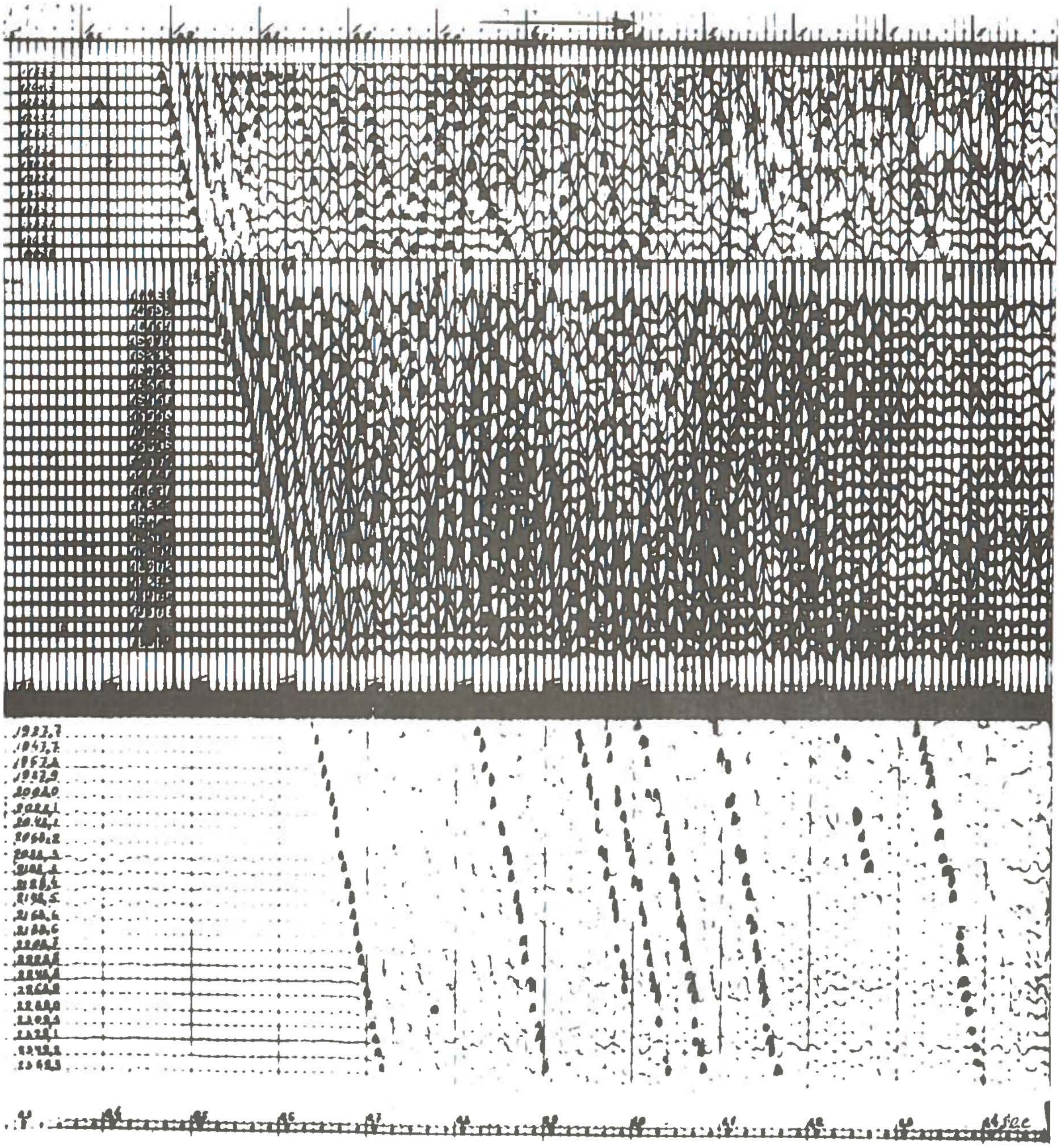

Fig 5a. Subtraction of incident waves at vertical seismic profiling in the borehole

Field record.

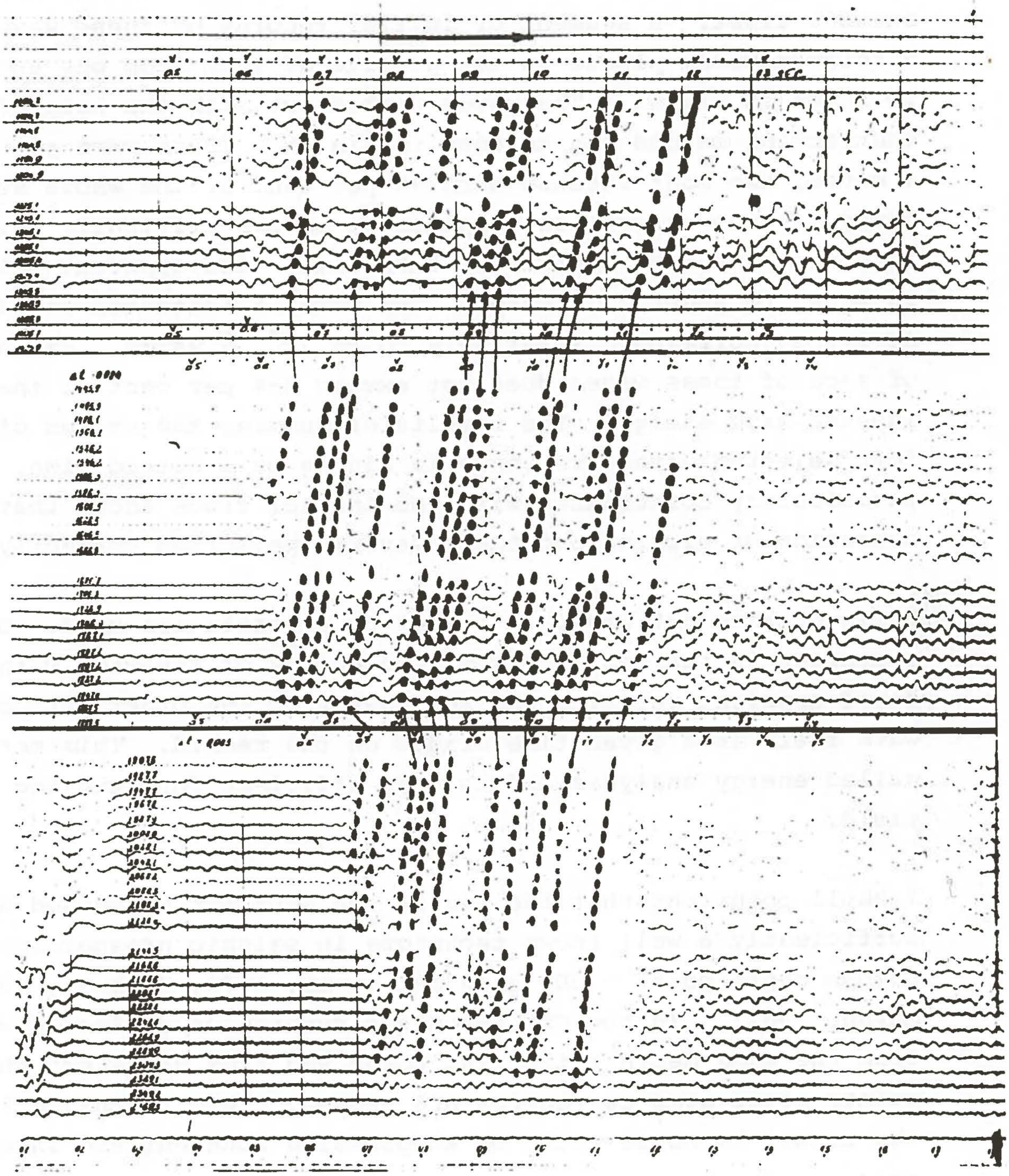

Fig 5b. Subtraction of incident waves at vertical seismic profiling in the borehole
Reflected waves after subtraction of incident waves.

The subtraction method was also used in seismology for picking out interfering waves connected with structural boundaries in the earth's crust. A segment of initial records of these waves by 5 seismometers, placed on the profile of 5 km from one another is shown in Fig 6a. The waves picked out with the help of the subtraction method can be seen in Fig 6b. There were picked out 4 waves, the most intense with 90 per cent of the whole summing energy on the record, corresponds to an overcritically reflected wave from the Moho boundary - PnPn wave. Its apparent velocity is equal to about 7.7 km/sec. The waves illustrated on S2, S3, S4 traces correspond relatively to Pn, P^{x}, $\overline{P}$ waves. The energy of each of these waves does not exceed 3-4 per cent of the most intense wave energy! The results of summing the traces of the four selected waves are shown in Fig 6a by a dotted line. Their satisfactory coincidence with the initial trace shows that the operation of picking out the waves was performed correctly.

While picking out waves, a number of criteria are used. One criterion is the ratio between the energy of the wave with a fixed apparent velocity and the energy of the other part of the wave field in a given time window on the record. This method is called energy analysis and is very efficient for studying the wave field.

I shall point out that the use of the subtraction method adds sufficiently a well known technique in seismic prospecting of a common depth point - CDP (Levjant et al, 1970, Meshbai, 1968, Mayne, 1962). In the CDP technique records of reflected waves from the same depth reflecting point and from different shot points after some correction are summed. This technique increases the signal to noise ratio by suppressing coherent and incoherent noise.

Using different multistep complexes of processing is reasonable for seismic array station data as well as in seismic prospecting. As one such complex may be suggested phased summation with different time delays for determining wave composition of the record, subtraction of coherent noise with following phased summation of the useful signal and filtering in the spectral window. If successive explosions at the same point occur or if earthquakes occur in the same zone, it is reasonable

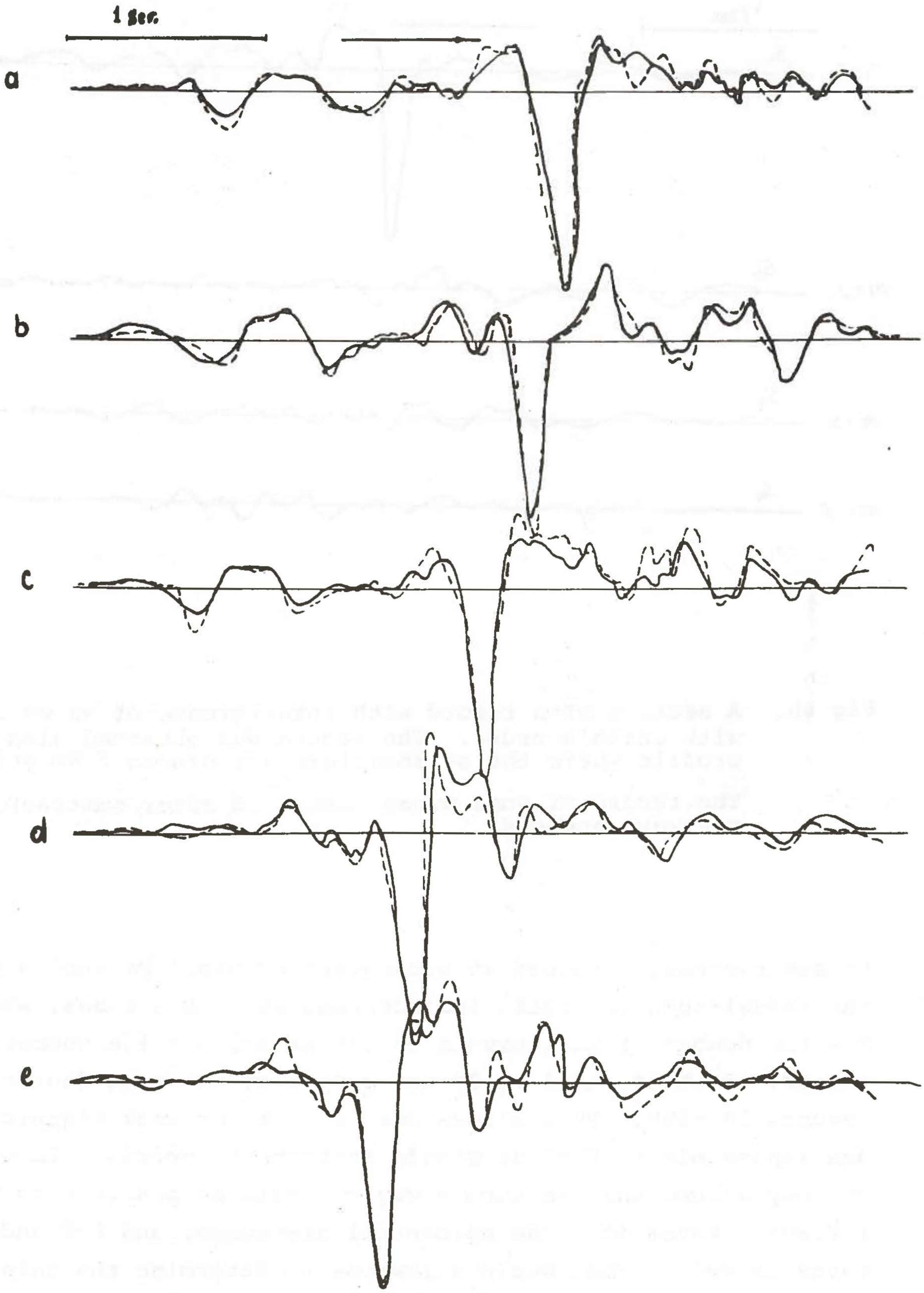

Fig 6a. A section of a record with interference of waves connected with earth's crust. The record was obtained along a profile where the seismometers are placed 5 km apart.

Initial records: a-e (continuous lines)

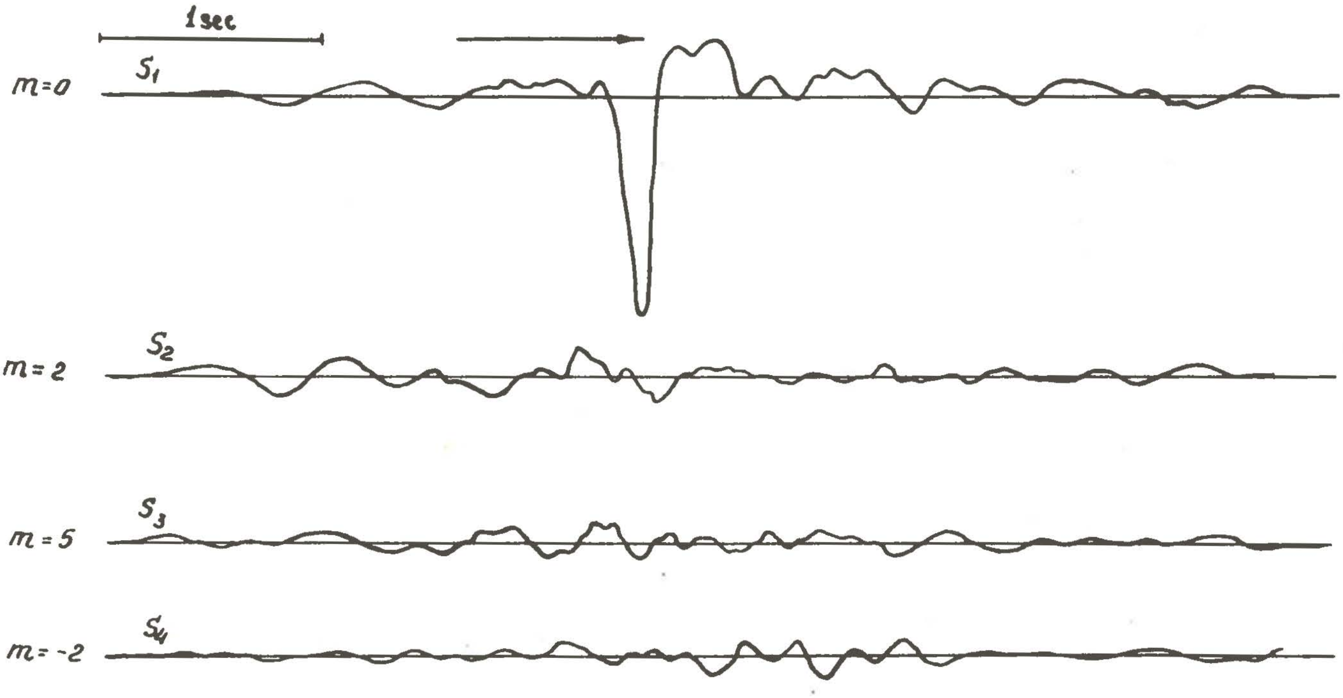

Fig 6b. A section of a record with interference of waves connected with earth's crust. The record was obtained along a profile where the seismometers are placed.5 km apart.

The record of some waves, obtained after subtraction, m = wave numbers.

to sum records, obtained at subsequent events. By such a process the signal-to-noise ratio is increased about M·n times, where M = the number of instruments in the group, n = the number of events. If M is equal to 20 and n to 5-10 the gain factor reaches 100-200. This allows one to pick out weak signals that are impossible to find at single instrument records. In particular one may assume that in such a way it would be possible to pick out reflected waves at close epicentral distances, and PcP and PnPn waves as well. That would allow one to determine the thin structure of the transition zone from the mantle to the core and from the crust to the mantle.

ON MAGNITUDES

Practical estimation of seismic wave energy in the source and classification of seismic events is based on magnitudes. The latter are determined by the relation of maximal vibration amplitudes to the period measured in P, PP, S and LR waves. Some attempts are currently being made to produce corresponding estimates from LQ waves.

There is no doubt that it is better to estimate source energy not by the single relation of the amplitude to the period but by taking into account the whole seismic energy flow registered at this point. Unfortunately, today we are not able to switch to energy estimations mainly because we cannot evaluate either the divergence or the attenuation the waves along their propagation paths due to absorption properties and refraction and transition phenomena of the different boundaries in the earth. Also the dependence of the frequency on the coefficient absorption at different parts of the wave path is unknown. To do energy estimations from the magnitude, all the unknown factors mentioned above must be taken into account in experimentally calibrated scales and corresponding ratios between magnitude and energy. Obviously, direct methods of energy estimation will not be worked out very soon. That is why it is still desirable to develop magnitude estimation methods of seismic wave energy and on this basis to improve event classification methods. Unfortunately, the present state of magnitude determination by different methods and stations differ greatly. I wish to give you an example. Magnitude M_b estimates obtained by US networks and from European stations data, for instance, for shallow foci Japanese earthquakes reach more than 3 units of magnitude difference. Special statistical investigations by Japanese seismologists on 85 of the above-mentioned earthquakes draw the following picture. Deviations in magnitude estimates according to US stations data are at the level from -0.3 to -1.7 units of magnitude and according to the European station data from +0.3 to +1.7. The same results were obtained by seismologists from other countries. Magnitude M_b estimates turn out to be lower systematically compared with those evaluated on records of broad band instrumentation in average at 0.7 units of magnitude. Existing divergences in magnitude determinations change for the worse when comparing seismic data of different networks. They make it difficult to use statistical data previously accumulated and to characterize the seismicity of the earth as a whole and its separate regions. They also decrease the efficiency of the $M_S:M_b$ criterion for classification of seismic events. That is why the problem of magnitude has drawn special attention. As known today a special commission on magnitude led by professor B. Karnik was created at IUGG. Let us hope that the commission will find solutions which will eliminate the present abnormal situation in the determination of magnitudes.

It seems to me that the problem can be solved sooner if we study the physical nature of the phenomenon and explain the reasons which cause the distortion of seismic wave records. These reasons can be divided into two groups. To the first group can be assigned those factors which we are not able to change, i.e., which are due to the nature of the phenomenon itself. They are: spectral contents of the vibrations (depending on the source mechanism and its intensity and depth), the asymmetry of the energy radiation pattern, change of the medium properties along the wave path affecting differently the dynamic parameters of longitudinal, shear and surface waves and some others. To the second group we can assign the factors which we are able to change to a certain degree, that is, instrument parameters, the installation conditions of seismometers, etc. However, in order to choose the latter parameters correctly and eliminate problems related to the installation conditions of the seismometers, it is necessary to know the dynamic characteristics of the recorded waves, their spectral content, character of wave polarization, the expected emergence angles and apparent wave velocities as well as the velocity and density properties of the upper section of rocks in the vicinity of the station. I shall touch only the following questions; namely, the distortion of the body wave by narrow band instrumentation and the filter properties of a low velocity upper layer.

Instrument Distortion

Trying to decrease noise level and in such a way to provide the possibility of detecting weak events with $M_b \leq 4$ at seismic stations, one started using narrow band short-period instruments with magnification maxima at periods around 0.7-1.0 sec.

At some stations, including NORSAR, the maximum magnification is placed at the even shorter period range of 0.2-1.0 sec. At the same time spectral maxima for most earthquakes with M>5 are at the periods of 4-8 sec and more.

As a result it turned out that the spectral band of recorded signals lies beyond the limits of the instruments' frequency band. It leads to great distortions of amplitude and period of body waves. That is why it is very difficult and often impossible to restore the real ground motion of seismic waves in such cases.

Thus, the seismologists agree to distort the records in their attempt to increase the effective sensitivity of the instruments in order to decrease the magnitude threshold for detecting events. However, simultaneously there were not worked out proper methods for providing the correct determination of the real ground motion. So the problem of magnitudes arose. How to solve this problem? The most radical solution could be to switch to recording seismic vibrations by broad band instrumentation with a large dynamic range of about 100-120 decibel, which is quite realistic using digital recording on magnetic tape. In this case it would be possible to transfer the process of picking out useful signals immersed in the noise to the stage of computer processing where it is possible to use some methods that do not distort the records as much as narrow band instruments, for example, digital filtering, coherent noise subtraction and some others. In this context, using array stations provided with broad band instrumentation seems to open new possibilities. Such stations are likely to be constructed in the near future. But what shall we do now? In my opinion, it is desirable, if possible, to determine magnitudes using the records obtained with relatively broad band instruments and not to use for this purpose data from stations which decrease magnitude values a great deal, for example, the US array stations. For this purpose it is better to choose a number of such stations in different countries and to use their data for routine determination of magnitudes in international seismological centers. It would be necessary to state for the chosen stations corresponding station corrections, which may vary for different epicentral distances due to changing spectral media responses depending on the signal emergence angles.

Influence of Seismometer Installation Conditions

It is shown in corresponding calculations made by the author together with I.S. Berzon and D.D. Sultanov (under the programs described by Ratnikova and Levshin, 1967) and other authors, that when seismometers are installed at places where basic rocks with high velocity layers are covered with low velocity material, records of P and S waves are greatly distorted. Examples of real velocity sections (models I,II,III) for which the calculations were made are presented in Fig 7. Along the vertical axes the depths of layers are shown, and along the horizontal axes the velocity values of P and S waves in km/sec and density ρ in g/cm^3.

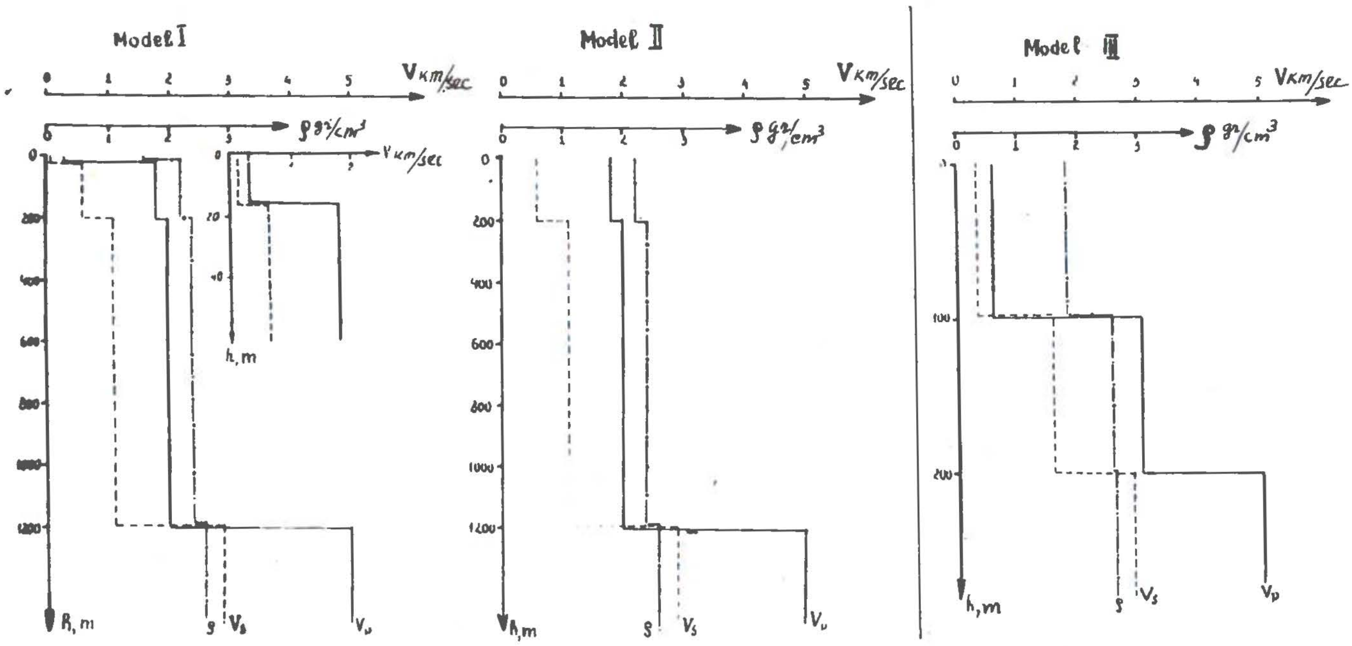

Fig 7. Velocity and density upper models for the uppermost part of the crust.

In Fig 8 and 9 there are shown corresponding examples of calculated seismograms of P waves for two velocity models, the first representing rocks with low velocity upper layer and the second without such a layer. The calculations were performed for ground displacements for three kinds of impulses of P waves impingeing on the boundary of high velocity rocks and overlaying sediments.

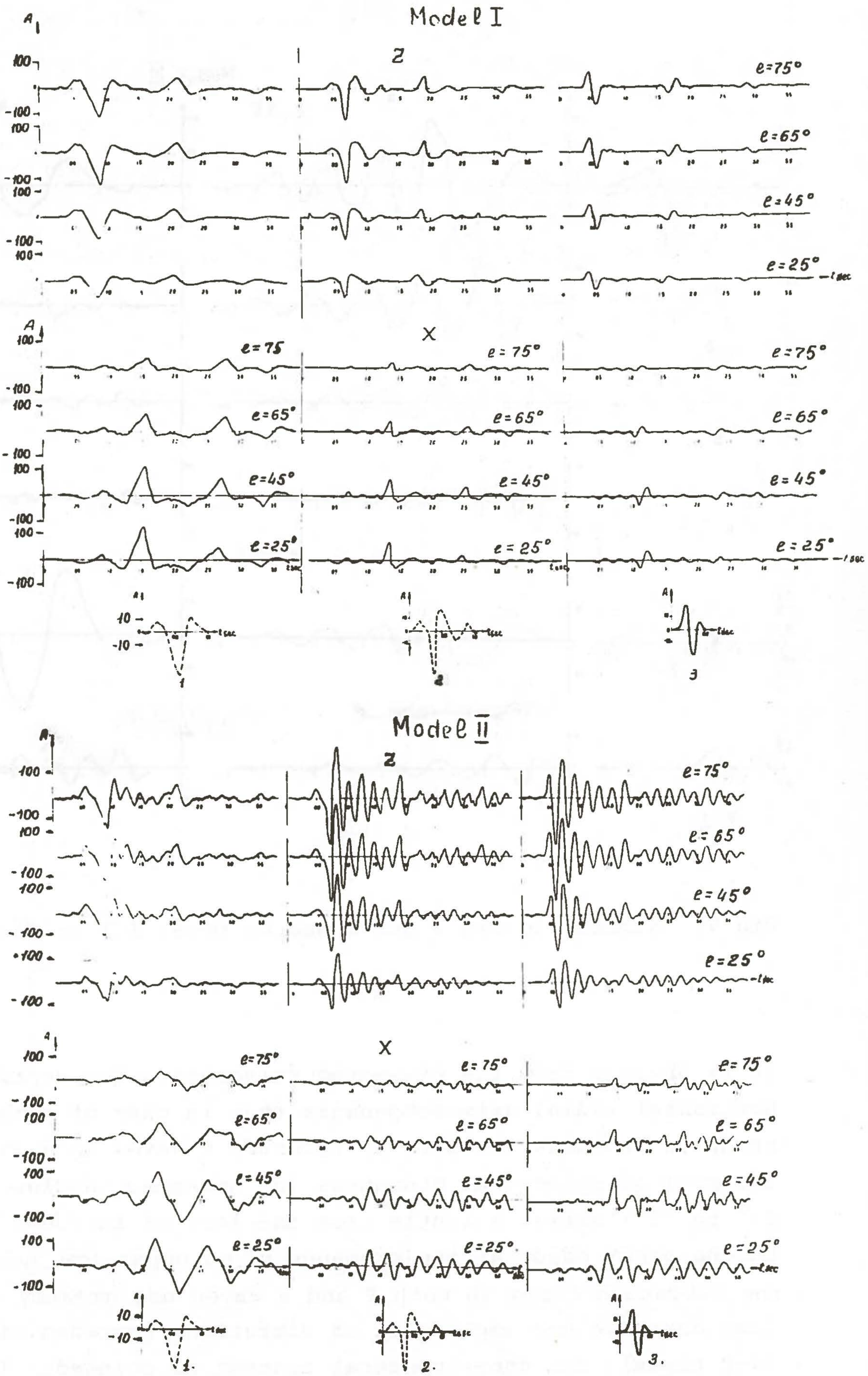

Fig 8. Synthetic seismograms, illustrating the effects of spectral medium response on the for of the P waves record: (Z is vertical and X is horizontal radial components)

a) without upper low velocity layer (Model I),
b) with upper low velocity layer (Model II).

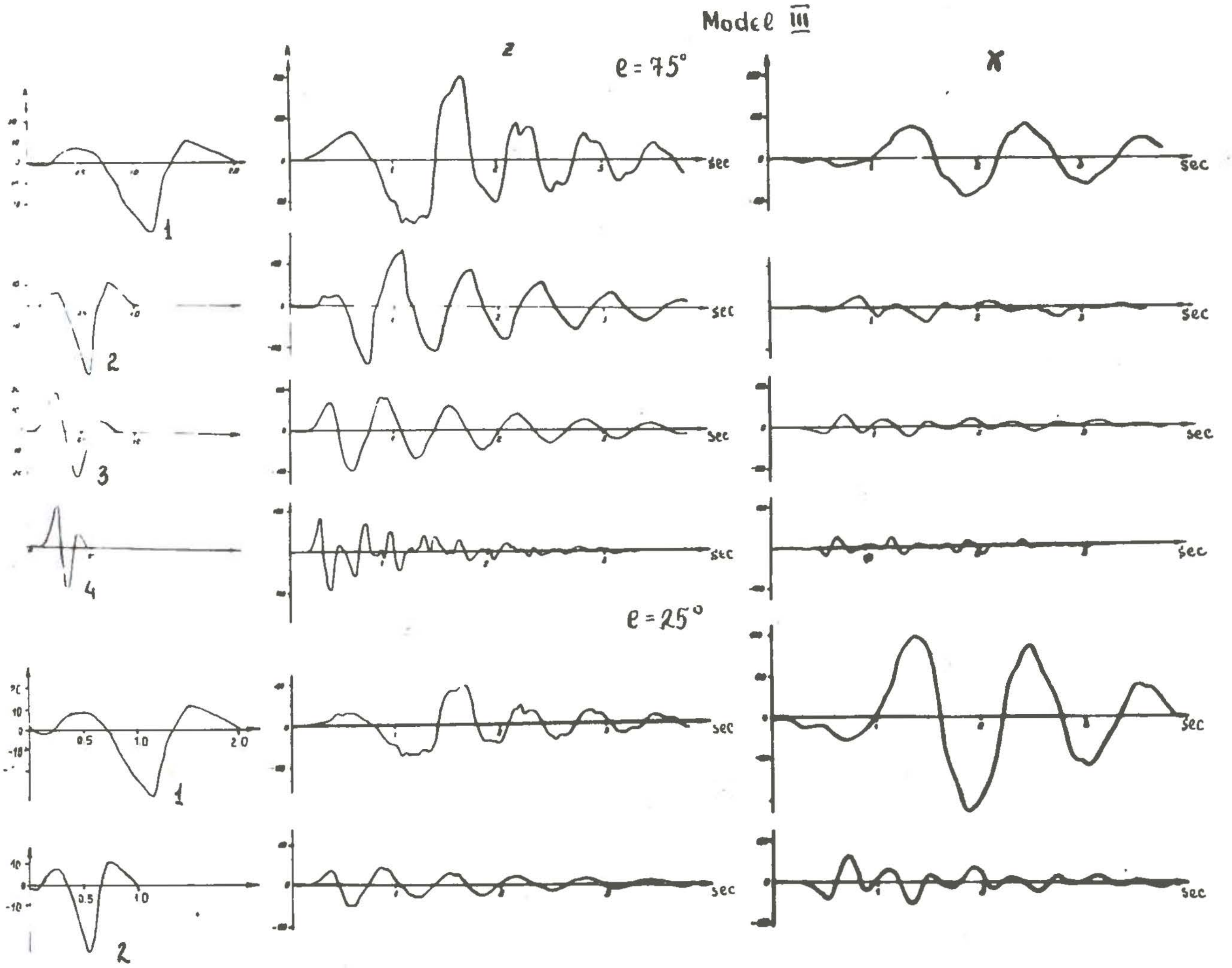

Fig 9. Similar to Fig 8 but based on Model III in Fig 7.

It is obvious from the presented seismograms for vertical and horizontal radial axis components that in case of seismometers being on bedrocks the form of recorded P waves in a wide interval of epicentral distances (of emergence angles e from 25° to 75°) differ slightly from the form of incident impulses. On the other hand, at the presence of an upper low velocity layer the vibration forms in both P and S waves are greatly distorted. Time duration and amplitudes of vibrations increase significantly (4-8 times), and their spectral content is changed. These distortions are caused by the resonance character of the spectral response of the medium, thin upper low velocity layer being a filter of a certain kind. Examples of spectral responses for the two models presented here are shown in Fig 10 and 11.

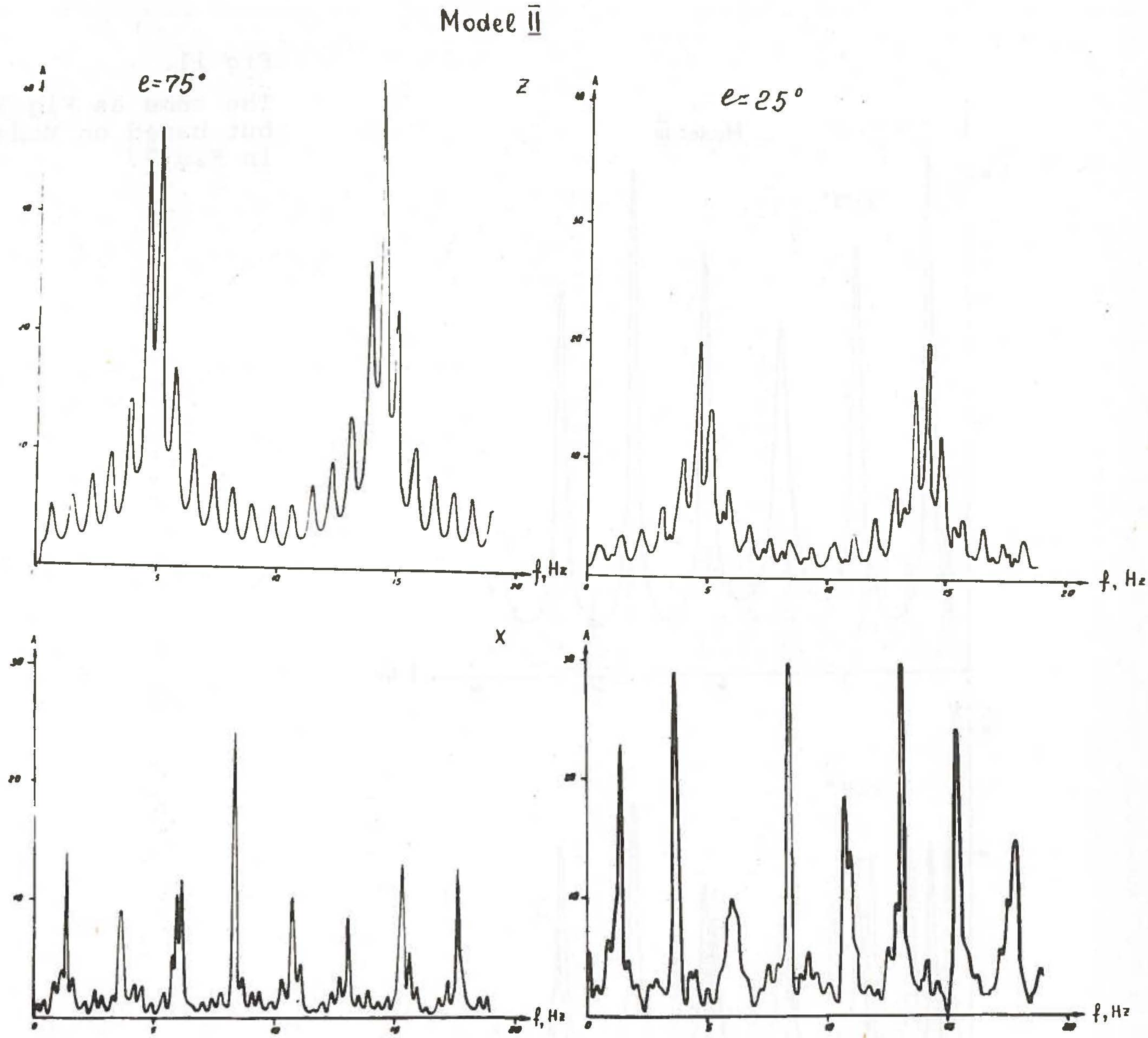

Fig 10. Spectral responses of the medium for angles of emergence a = 75°, b = 25°, Z and X = vertical and horizontal components. Model II in Fig 7 is used.

Spectral responses differ greatly for vertical and horizontal components of ground motion. This leads to the difference in the records of vertical and horizontal seismographs. The shape and amplitude distribution of spectral responses are changing depending upon the emergence angles, which is easily seen in Fig 10 and 11. The comparison of theoretical results with experimental data demonstrates a reliable similarity.

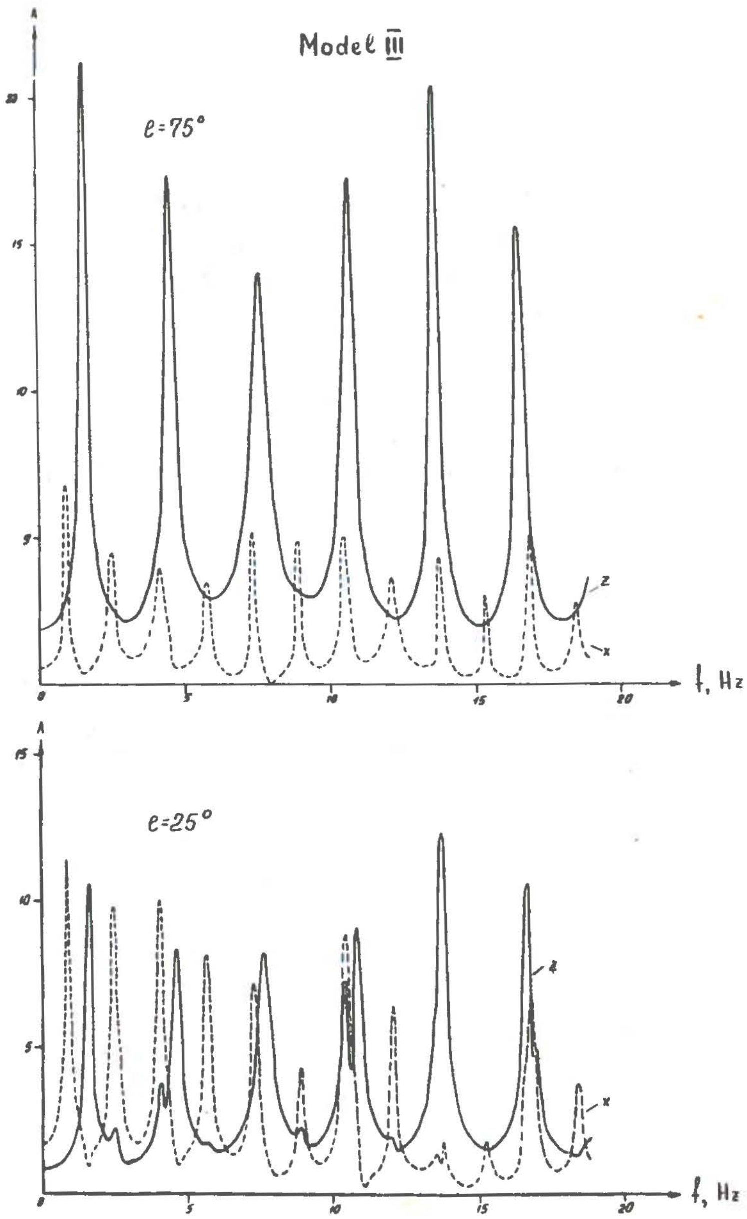

Fig 11.

The same as Fig 10 but based on Model III in Fig 7.

Thus the following conclusions may be drawn from the above considerations. In order to decrease the randomness in the computed M_b values at different stations, they must be situated on bedrocks at such depths where the rocks have not been weathered greatly. Such rocks in granite massive usually lay at the depth of 40-50 m (Duclaux, 1969). The choosing of identical conditions for the installation of seismometers at array stations is a matter of special importance.

CONCLUSION

The application of processing methods developed in seismic prospecting to array stations shows great possibilities in increasing the efficiency of these stations. However, in order to realize this potential fully it seems necessary to change the amplitude-frequency responses of the instruments used at array stations by broadening their frequency band. Special attention must be given to the selection of the sites where stations are to be situated and to the conditions for the installation of the seismometers.

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