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The Wave Field Associated With a Fine Structured Moho in Continents and Oceans

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Abstract. The crust-mantle transition zone in continents and oceans is regarded as a complex block-layered structure. The case of blocks of small dimension may be described by a thin-layered zone with random distribution of its seismic parameters. Such structure accounts for continuous and well correlated subcritical reflections whose amplitudes are 3–4 times higher than those of a first order velocity discontinuity. The reflectivity from the random zone is practically independent of frequency above 10 Hz. If the dimensions of the blocks are large the subcritical reflections may be correlated as discontinuous branches of the travel-time curve with various amplitudes on them.

Key words: Crust-mantle transition – Thinlayered zone – Spectra – Reflectivity – Travel-time and amplitude-distance curves.

During the past decade great attention was paid to the investigation of the fine structure of the Moho-boundary beneath continents. In some regions the crust-mantle transition may be strongly layered and can be represented by thinlayered zones (Fuchs, 1970; Fuchs and Müller, 1971; Berzon et al., 1975; Davydova et al., 1972; Pavlenkova, 1973). It was shown that dynamic analysis (amplitudes, spectra, wave form) of reflections in the sub-critical area is most efficient for the study of the structure of thinlayered zones.

Until recently deep seismic sounding (DSS) studies in oceans have been based on frequencies of about 5 Hz, i.e., on wave lengths comparable with the total thickness of the oceanic crust. The wave field was observed in critical and overcritical areas. All these factors hindered the investigation of the thinlayering of the oceanic crust and upper mantle. The utilization of airgun sources in marine DSS studies now makes it possible to expand the frequency band (20–30 Hz) and to obtain better correlations: this is important for the detection of subcritical reflections in the second arrivals. The statistical analysis of data obtained from airguns and shots shows considerably thinner layering of both the upper and the lower parts of the oceanic crust (Kosminskaya and Kapustian,

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1975). The use of airguns in marine studies enables us to investigate the thinlayering of the oceanic crust and especially the crustmantle transition. This is important for the study of the processes of formation and development of the oceanic crust.

In continents the structure of the crust-mantle thinlayered transition was generally supposed to be horizontally continuous. Such models accounted for those peculiarities of the wave correlation which could not be explained by simple first order discontinuities or gradiental transition zones. Nevertheless it is difficult to imagine such stability of individual layers within the transition zone over horizontal distance of dozens of kilometers. The assumption of variable layer parameters is more realistic. Investigations of the discontinuous wave correlation or the dashed character of the crustal wave field will show the complex micro- and macro-block-layering of the crust: thus it may be possible to study the complex block-layered crust-mantle transition. Hence it is important to assess the chances for the detection of thinlayering and micro-blocked structure of the Mohorovičić zone and to develop the DSS method in continents and oceans appropriately.

Theory tells us that reflection dynamics depend not only on the structure at the reflection point but on the properties of the media in the vicinity of this point, limited by the effective section of the ray tube[1]. The linear dimension of this effective section is proportional to $\sqrt{\lambda L}$, where λ is the wave length and L is the ray length, i.e., the dimension is transformed in terms of the boundary depth and epicentral distance. In continents the linear dimension of this area is about 10 km for the reflection from the Moho (depth 40 km) observed at a distance of about 10 km from the source (Davydova et al., 1972). This dimension of the ray tube for the oceanic crust (Moho-depth 10 km) is about 3 km and increases with epicentral distance from the shotpoint. Such calculations make it possible to divide the supposed block-layering of the Moho into two types:

(1) micro-block-layering; i.e., the horizontal dimensions of the blocks are less than the whole reflectivity area;

(2) macro-block-layering, i.e., the transition zone consists of blocks of the same dimension as the reflectivity area. The layering structure is stable within an individual block.

The case of micro-block-layering is represented by a thinlayered zone with a random distribution of its seismic parameters. It is possible to imagine such a structure as a mixture of small lenses whose velocity and thickness are derived from a normal distribution. The computational methods for such media were developed in seismic prospecting (Berzon et al., 1973), and were discussed in the paper by Davydova et al. (1972) for the continental DSS data for the subcritical area.

Here we investigate such thinlayered zones not only for continents but also oceans and discuss dynamics for all distance ranges – subcritical, critical and overcritical – to choose the optimal frequency and distance ranges for observation of blockthinlayered zones.

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[1] The effective section of the ray tube is the area obtained from the intersection of the ray tube and the boundary or the part of the boundary within the ray tube

The random layered zone structure is determined by the random parameters of the layers: thickness $h_n (1 \leqq n \leqq N)$, P- and S-wave velocities $V_{p,n}$; $V_{s,n}$ and densities ρ_n. We consider the normal law of layer parameters distribution. It is possible to construct a random vector $\vec{\beta}$ with coordinates equal to the layer parameters

$$\beta_{4n} = V_{p,n}; \quad \beta_{4n+1} = V_{s,n}; \quad \beta_{4n+2} = h_n; \quad \beta_{4n+3} = \rho_n.$$

In the case of the incident plane P-wave pulse

$$F_p(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S(\omega)\, e^{i\omega t}\, d\omega,$$

where $S(\omega)$ is its spectrum, the P-reflection from a thinlayered zone will be as follows

$$F_{pp}(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S(\omega)\, \eta_0(\omega)\, e^{i\omega t}\, d\omega,$$

where $\eta_0(\omega)$ is the reflectivity for this zone. It is calculated by the well-known reflectivity matrix method (Ratnikova and Levshin, 1967; Fuchs, 1968). In the case of a random thinlayered zone, the random reflection for the wide incident wave conditions will be as follows

$$f(t, \vec{\beta}) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S(\omega)\, \eta(\omega, \vec{\beta})\, e^{i\omega t}\, d\omega,$$

where $\eta(\omega, \vec{\beta})$ is the reflectivity for random zone and random function of frequency ω and

$$M[f(t, \vec{\beta})] = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S(\omega)\, M[\eta(\omega, \vec{\beta})] e^{i\omega t}\, d\omega.$$

We calculated $M[\eta(\omega, \vec{\beta})]$ for $L = 30$ realizations. Each individual realization was a thinlayered zone whose parameters were an individual realization of vector $\vec{\beta}$. The reflectivity for each individual realization has been calculated and after that the reflectivity for the random zone was obtained by the formulas:

$$M[\eta(\omega_\kappa, \vec{\beta})] = \frac{1}{L} \sum_{l=1}^{L} \eta(\omega_\kappa, \vec{\beta}_l);$$

$$M[|\eta(\omega_\kappa, \vec{\beta})|] = \frac{1}{L} \sum_{l=1}^{L} |\eta(\omega_\kappa, \vec{\beta}_l)|.$$

In this paper the thinlayered random zone is regarded as a model of the Moho in continents and oceans. The mean velocity in the random zone (8.2 km/s) is approximately equal to the value in upper mantle (8.0 km/s) and differs greatly from the value in the crust (7.0 km/s). The dynamics for such a structure is calculated in subcritical, critical and overcritical areas and is compared with the computations for individual relaizations and an equivalent layer (the layer whose parameters are equal to the mean values for the random zone $V_p = 8.2$ km/s; $h = 1.1$ km).

Figure 1 represents the depth-velocity models (Fig. 1C), the cross-section (Fig. 1B) of the micro-block-layered M-boundary and the dynamic travel-time curve[2] for the M-reflection $P^{8.0}_{\mathrm{refl}}$ (Fig. 1A). In the case of 30 realizations the dimension of each micro-block (the block which layer thickness and velocity are stable) has to be approximately 100 m for oceanic and 300 m for continental crust. The reflection from such a structure will be correlated continuously and its amplitude near the shot point will be 3–4 times greater than those for the equivalent layer.

The frequency characteristics of the micro-block-layered M-boundary reflection are shown in Fig. 2. The amplitude spectra of the reflected wave (reflectivity) depend on the epicentral distance and frequency. The sets of spectra may be divided into 3 zones: subcritical, critical and overcritical.

In the subcritical zone (from 2 to 70 km in continental DSS studies 0.5 to 20 km in oceans) the amplitude spectra increase approximately linearly with frequency up to 5 Hz. Within the higher frequency band spectra oscillate slightly (15 %) around the average value independent of the frequency and decrease as distance increases.

In the critical zone (70–150 km in continents, 20–40 km in oceans) spectra increase with frequency, the fastest increase being up to 10 Hz. The location of the critical point in this area is moved towards smaller distances for higher frequencies. This phenomenon is known (Červeny and Ravindra, 1971) to be determined by the relationship between the wave length and the thickness of the layer. This fact should be taken into account in the choosing of the optimum frequency and distance ranges in the modern critical-angle-reflection studies in oceans.

In the overcritical zone (greater than 150 km in continents, 40 km in oceans) the amplitude spectra are practically independent of frequency. Thus overcritical reflections are not suitable for the determination of fine structure.

Figure 3 shows the comparison of the spectra for a random zone, an equivalent layer, individual realizations and a simple first order boundary in the subcritical (Fig. 3B), critical (Fig. 3C) and overcritical (Fig. 3D) zones. In subcritical and critical zones spectra of individual realizations are of the complex resonance form with alternation of sharp maximum and minimum. The spectrum of the equivalent layer is of a sine form oscillating around the reflectivity for a first order discontinuity. In the overcritical zone spectra for all M-boundary models are practically independent on frequency. Curves 2 and 3 (Fig. 3) show that the spectra of individual thinlayered zones (zones whose structure are stable within the profile) vary greatly with epicentral distance. Such a phenomenon shows the difficulty in comparing spectra obtained at different distances to determine a boundary model. Spectra for a micro-block layered M-boundary (curve 1, Fig. 3) are not of a resonance form and are stable within the profile in contrast to the case of individual realizations.

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[2] The dynamic travel-time curve is a combination of an amplitude distance curve and a travel-time curve. The amplitudes are plotted above the travel-time curve

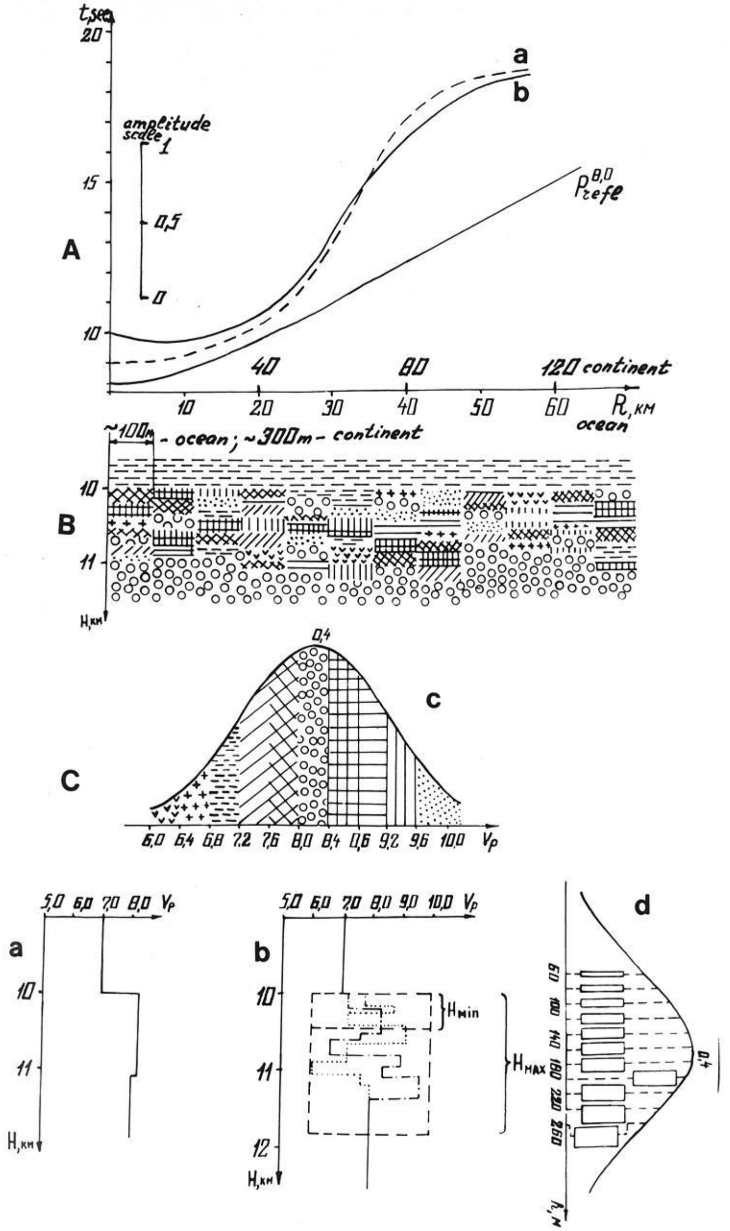

Fig. 1A–C. Dynamic travel-time curve (**A**), cross-section (**B**) and velocity-depth models (**C**) of the micro-block-layered structure of the M-boundary in continents and oceans: *a* equivalent layer, *b* random zone; *c* velocity and *d* thickness distribution in the individual layers of random zone

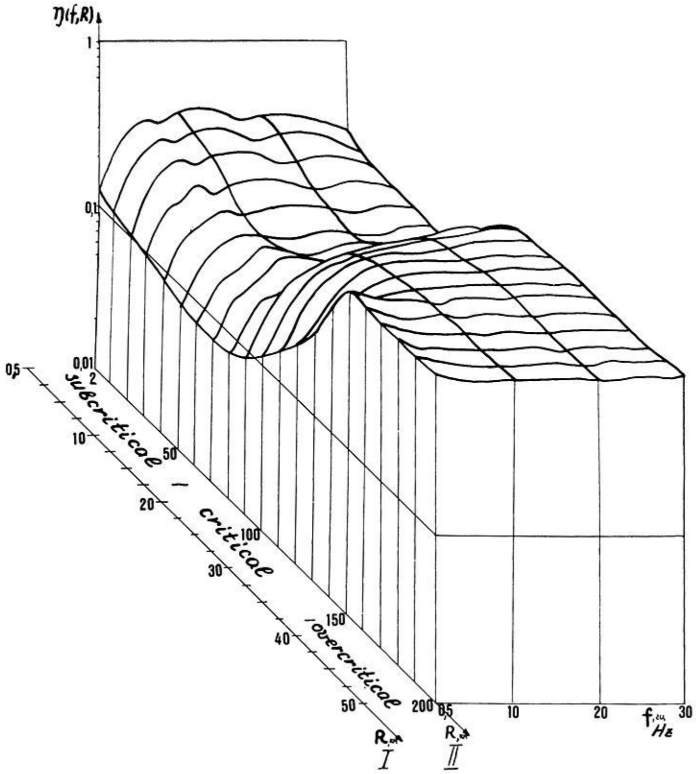

Fig. 2. Block-diagram of the amplitude spectra of a random zone in oceans (*scale I*) and continents (*scale II*)

In Fig. 4 the dependence of reflectivity on epicentral distance studies are shown at 10 Hz (DSS studies in continents) and 30 Hz (airgun studies in oceans) for the same M-boundary models as in Fig. 3. For individual realizations the curves in Fig. 4 correspond to the amplitude-distance curves obtained with a narrow band-width pulse. Such pulses are typical of non-explosive sources: airguns, sparkers, etc. In this case subcritical and overcritical reflections may be characterized by great variation in amplitudes and by interruptions of the phase correlation. Interruption in wave correlation may also occur in the case of stable thinlayered zones due to amplitudes falling below the noise level (in Fig. 4 the noise is dashed). Therefore if the source pulse is of narrow band-width form such interruption of subcritical reflections can be observed even if the structure of the thinlayered zone is horizontally homogeneous and stable.The reflections from a micro-block-layered M-boundary (curve 1, Fig. 4) are stable within the whole profile and frequency band. The amplitudes in the subcritical area are 3–4 times higher than those of a first order discontinuity or the equivalent layer.

In Fig. 5 the change of wave form with epicentral distance for reflections from a random zone and from an individual realization is shown. The pulse has a wide-band width with the main frequency 10 Hz. Figure 4 shows the energy redistribution towards the first phases: the wave pattern becomes relatively

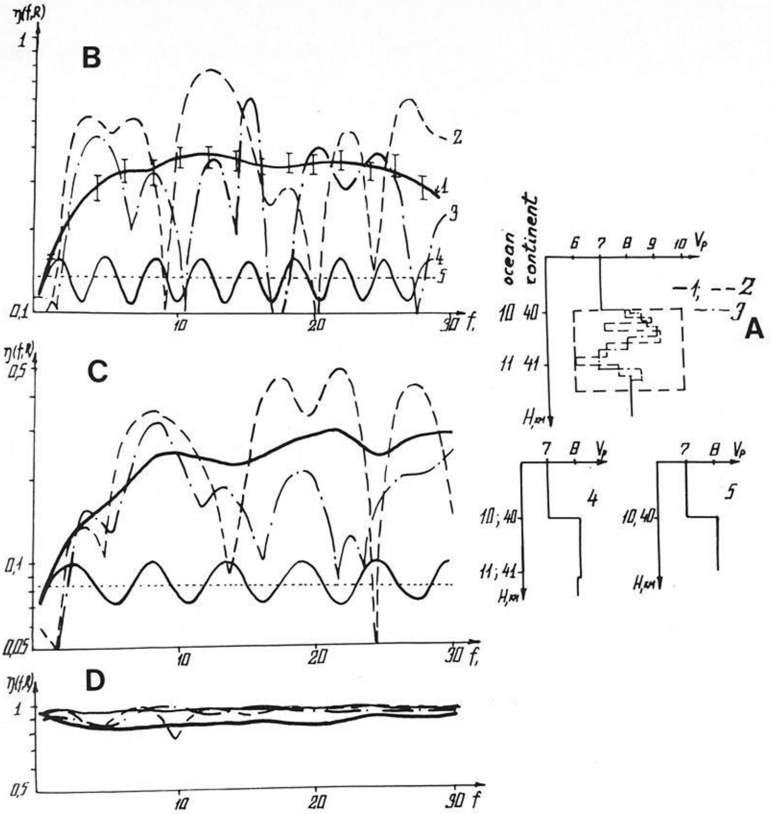

Fig. 3A–D. M-boundary models (**A**) and their spectra in subcritical (**B**), critical (**C**) and overcritical (**D**) areas: *1* random zone; *2*, *3* its individual realizations, *4* equivalent layer, *5* first order discontinuity. In *curve 1* (Fig. 3B) the dispersion level $3\sigma/\sqrt{L}$ is shown

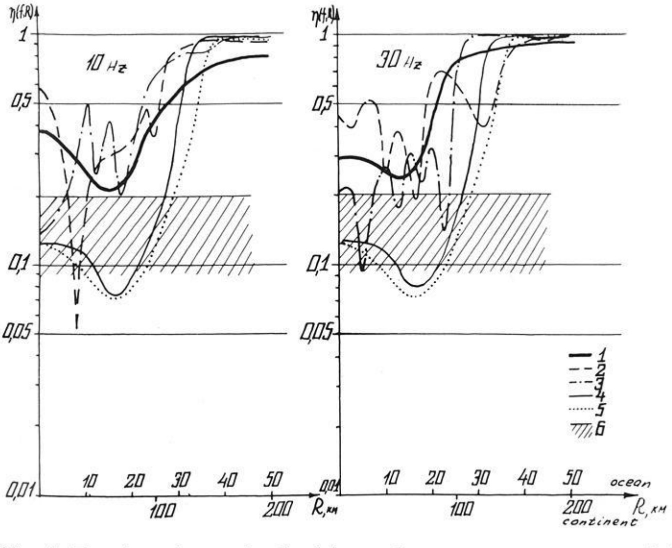

Fig. 4. The dependence of reflectivity at frequency components at 10 Hz and 30 Hz and on the epicentral distance for M-boundary models: *1* random zone; *2*, *3* its individual realizations, *4* equivalent layer, *5* first order discontinuity (models see in Fig. 3); *6* possible level of the second arrivals

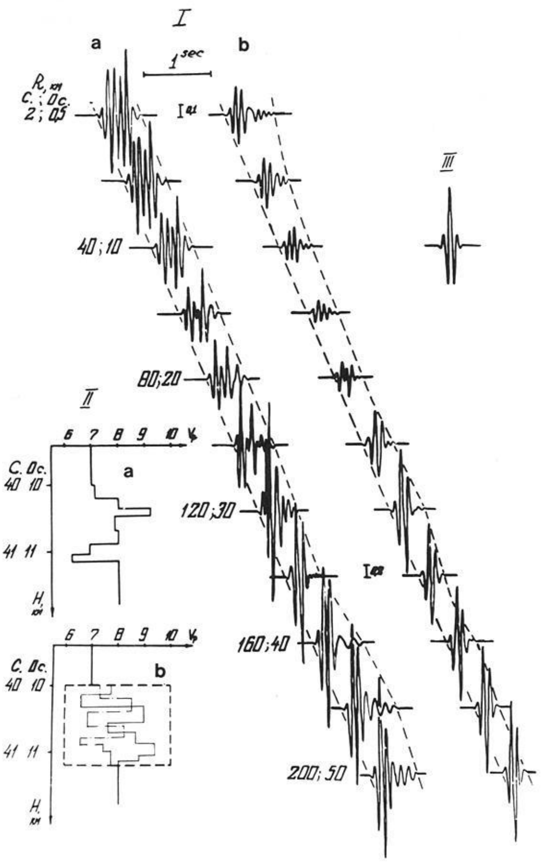

Fig. 5. The synthetic seismograms (*I*) for the reflections of M-boundary models (*II*): *a* individual realization and *b* random zone. (*III*) Incident pulse

shorter. It may be noticed that near the shot point the length of the reflection is 2–3 times greater than those of the incident pulse: this fact should be considered when interpreting data obtained at these distances using non-explosive sources. Analysis of the change in wave pattern shows that in the case of a thinlayered zone that is stable within the profile, and using a wide-band pulse, the wave form is very unstable and phase correlation is difficult. If the transition zone is micro-block-layered the wave pattern will change weakly with distance and it will be possible to correlate individual phases.

The investigation of the dynamics of micro-block-layering reflections shows that such M-boundary structure gives strong and well-correlated subcritical reflections with nonresonance spectra. Up to now absorption (i.e., the frequency selectivity of the media) has not been taken into account. If one includes the influence of absorption and ray divergence it will be easier to compare the theoretical results with experimental data so as to adopt the best observational methods.

In Fig. 6A the block-diagram of amplitude spectra with absorption for $Q = 400$ (see Berzon et al., 1975) and ray divergence, $\frac{1}{R}$, is shown for micro-block-

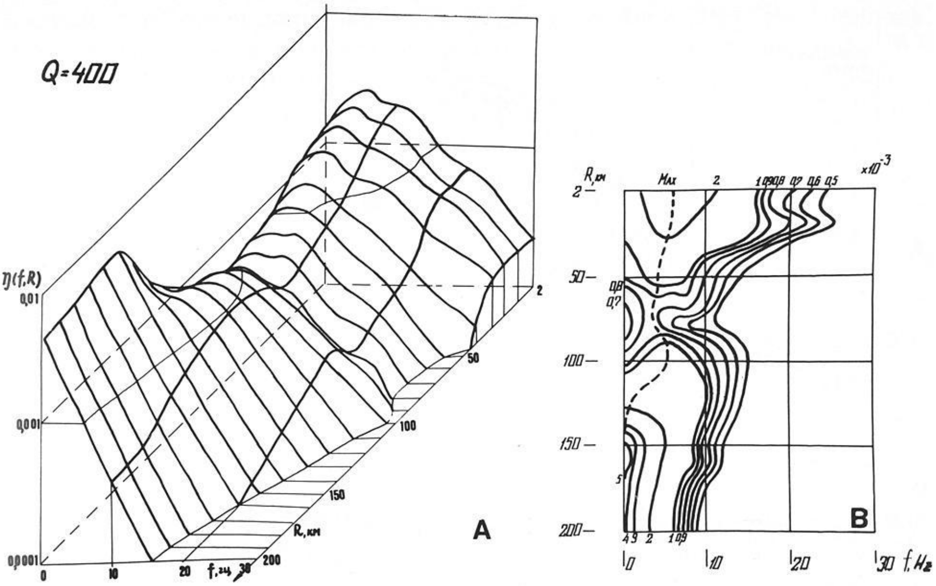

Fig. 6A and B. Block-diagram of amplitude spectra (**A**) with absorption $Q = 400$ and ray divergency 1/R for the reflection from random M-zone in continents. (**B**) The spectrum field for this surface

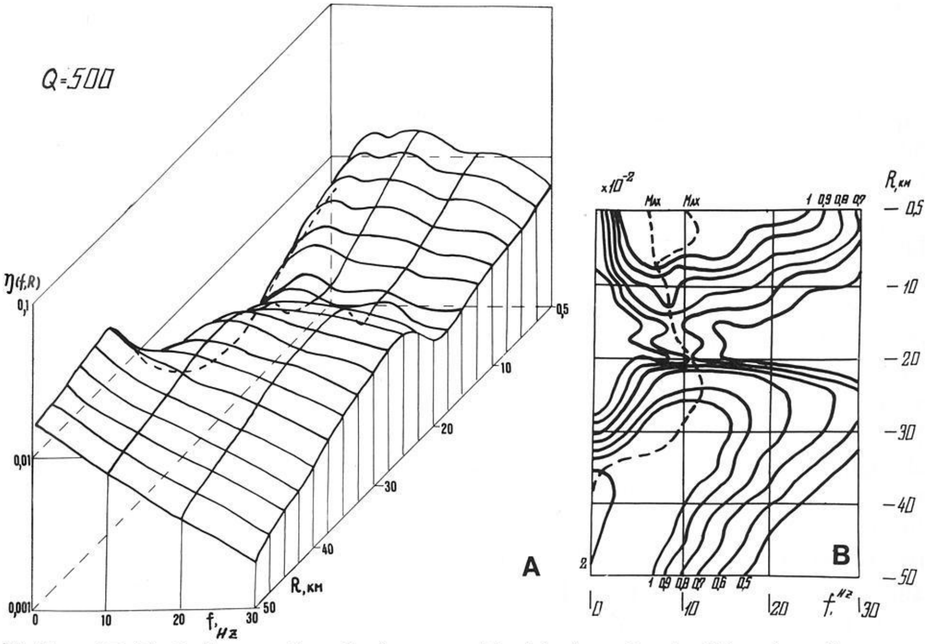

Fig. 7A and B. Block-diagram of amplitude spectra (**A**) with absorption $Q = 500$ and ray divergency 1/R for the reflection from random M-zone in oceans. (**B**) The spectrum field for this surface

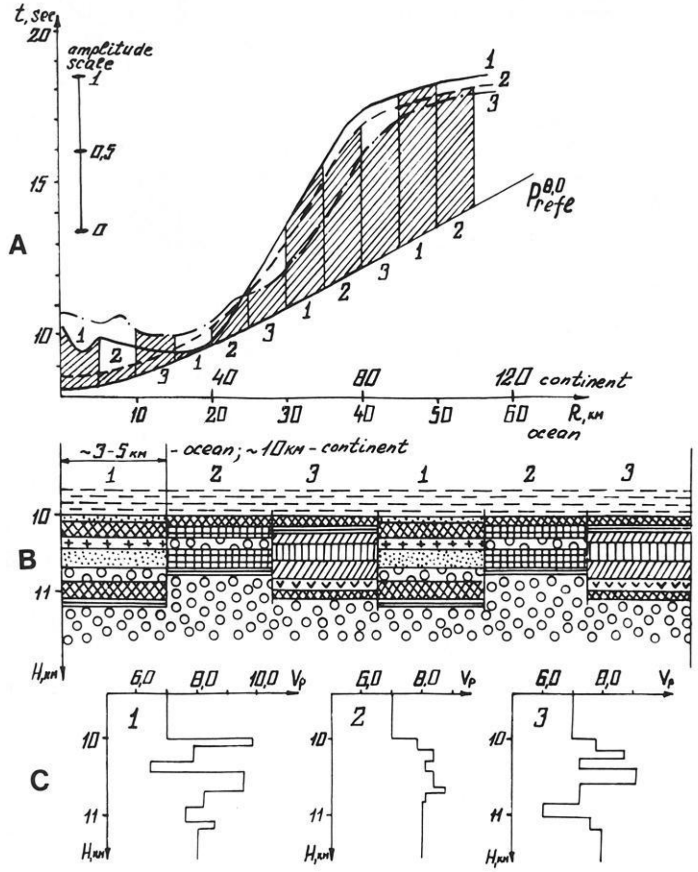

Fig. 8A–C. Dynamic travel-time curve (**A**), cross-section (**B**) and depth-velocity models (**C**) for macro-block-layered M-boundary in continent and ocean consisted of the altering of blocks 1, 2, 3

layered M-boundary in a continent. Figure 6B represents the spectrum field for this surface: the pulse spectrum was not considered, corresponding to the case of a wideband source or receiver. Figure 6 makes it clear that the amplitude spectra of a reflection acquires more sharp resonance due to the effect of absorption. The maximum of the spectrum occurs at 5 Hz in the sub-critical and critical zone and at the lowest frequencies of the incident pulse in the overcritical zone. Movement of the spectrum maximum shown in Fig. 6B corresponds to the changing of the main frequency that can be observed in records. It is evident that the visible frequency becomes lower in the overcritical zone as compared to those in subcritical ones. Such a peculiarity is due to the frequency features of the micro-block-layering of M-boundary and not to the interference of head and reflected waves in the critical zone.

It is clear from Fig. 6B that frequencies up to 10 Hz are the best ones to investigate micro-block-layering of the M-boundary in continental DSS studies. The utilization of higher frequencies even near the shot point will lead to a decrease in reflection amplitude. If the frequency is about 20 Hz the amplitude will decrease 3 times as compared to its maximum value near the shot point and therefore it will be more difficult to correlate reflections in the second arrivals.

In Fig. 7 the block-diagram of amplitude spectrum and spectrum field for a micro-block-layered M-boundary in oceans are represented. We assume $Q = 500$. As one can see from Fig. 7 the important peculiarity of reflection correlation is the great changes of visible frequency on records. The visible frequency increases from 6 Hz to about 12 Hz towards the critical zone and in subcritical regions decreases to the lowest frequency of the incident pulse.

Figure 7 shows that the best frequencies to investigate such structures in oceans are those of about 5–10 Hz. These frequencies are essential in marine DSS studies due to the difficulty of subcritical reflection correlation among the direct and multiple water wave arrivals. The utilization of airgun sources with frequencies 20–30 Hz decreases the possible amplitude level by a factor of 1.5–2 in the subcritical zone. In the critical zone the use of highfrequency sources (20–30 Hz) also decreases the possible amplitude by a factor of up to 2. This should be taken into account in considering the best frequency band for critical-angle-reflection-studies in oceans.

Now we come to the analyses of the wave field reflected from macro-block layered M-boundary in continents and oceans. The cross-section of such structure with altering of blocks containing thinlayered zones of types 1, 2, 3 is shown in Fig. 8. The dynamic travel-time curve (Fig. 8A) consists of pieces of dynamic travel-time curves for the individual blocks. As one can see from Fig. 8 the subcritical and nearcritical areas are rather informative for the investigation of fine M-boundary structure whereas the overcritical reflections are not in fact sensitive to such structure. The reflections may be characterized by both large pieces of interruptions of wave correlation (with dimension about the horizontal dimension of a block) and phase correlation discontinuities. In the first case the reflections from blocks with reflectivity lower than the level of second arrivals can not be seen. The phase correlation interruptions and the amplitude variations are connected with the reflectivity properties within the individual blocks (see the above-mentioned dynamic analysis of individual realizations). The branches of reflection correlation may be both equal and smaller or greater (see for example the nearcritical area) than the horizontal dimension of a block.

The representation of the M-boundary by thinlayered zones consisting of blocks of different dimensions accounts for the important dynamic and kinematic peculiarities of M-reflections.

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