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Vibroseismic research of Altai–Sayan region

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The paper considers the results of the 1995 Russian–Japanese experiment, in which the structure of vibroseismic fields of powerful sources, as well as the relation between these fields and the tensely deformed state of the geological medium were investigated.

1. Introduction

The progress of the use of vibroseismic methods in petroleum and ore prospecting seismology studying of sedimentary basins and regions with highly developed industrial infrastructure, where it is impossible to perform research with explosive vibration sources, is now universally recognized.

The role of vibrational methods has recently increased also when solving problems of deep geophysics and geodynamics, as caused by creation of high power fixed and movable vibrators with 60–100 tons force amplitude, that provide a monochromatic emission of seismic signals on several thousands kilometers. The special experiments conducted with 100-ton vibrator in Baikal rift zone have shown high stability of vibroseismic signals and recurrence of actions, what opens perspectives of the use of high-power vibrators at vibroseismic monitoring of focal zones of earthquakes and at study of variations of stress-deformed state of a medium of tectonic areas, etc. The results of vibroseismic research shown in the paper reflect only a small part of vibroseismic work done in Siberia and largely are devoted to study of wave field from a 100-tons vibrator on distances up to 300 km, optimum for study of the Earth's crust and upper mantle.

The region of research (Figure 1) is situated in concatenation zone of the West–Siberian plate with Altai–Sayan fold area. It covers a number of heterogeneous geological structures: Tom–Kolyvanskaya fold area, Salair ridge, Biysk–Barnaul depression and Gorny Altai.

In Russia Altai–Sayan region belongs to a number of areas with increased seismic activity. On instrumental data for the last 35 years more than 4000 seismic events with various intensity are noted within the boundaries of this region. Many of them have 11-power class with magnitude 4 and intensity

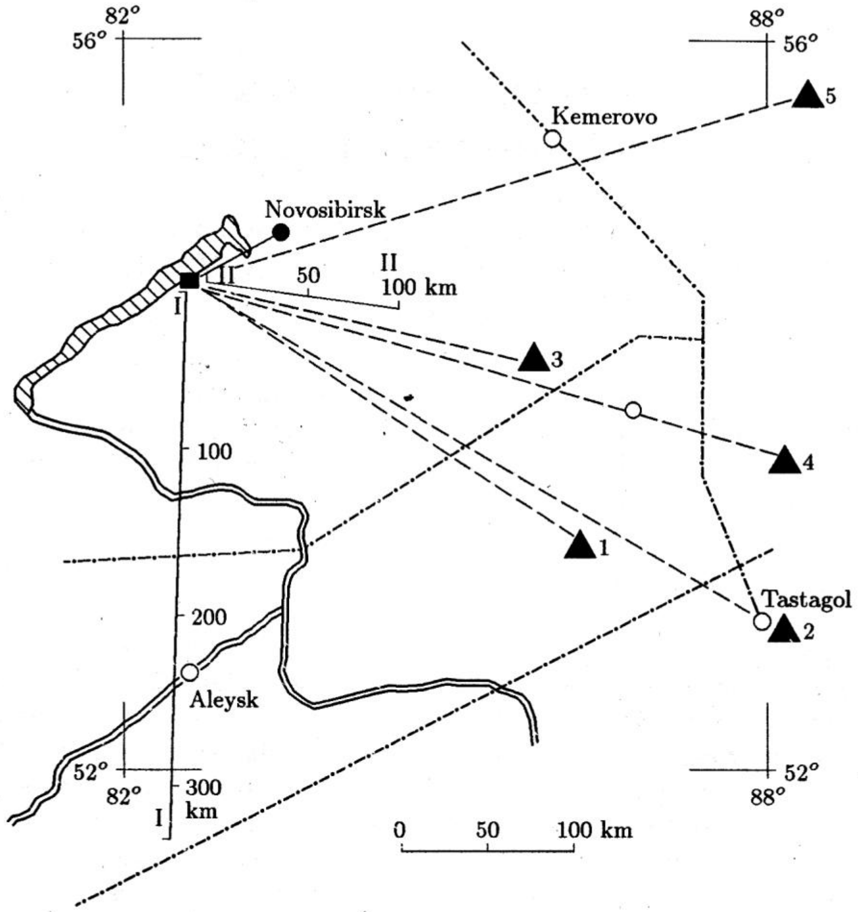

Figure 1. Scheme of seismical (vibroseismic and explosion) research in Altay–Sayan region: 1 – profiles DSS; 2 – vibroseismic profiles; 3 – vibroseismic sources; 4 – station for vibroseismic monitoring; 5 – points of recording for vibroseismic and explosion monitoring

of shaking of earth surface to magnitude 6–7 on the 12-magnitude scale MSK-64. Judging from macroseismic data on this territory a position of earthquake focuses with magnitude more than 6 is possible, an intensity of shaking of earth surface can reach magnitude 8.

In recent years on separate sites of Altai–Sayan region, the complex of geologo-geophysical research is carried out, as a result the information of a deep structure of region is obtained, the sites in the Earth's crust with significant horizontal heterogeneities on strain-strength properties are revealed, and correlation couplings of revealed heterogeneities with modern display of seismicity of territory are established.

The federal program of average- and short-term prognosis of earthquakes in industrial areas of Altai–Sayan region is worked out, a basis of which procedure regime seismological observations on area network and active vibroseismic monitoring of a medium form, making it possible to ensure an operating control over the development of seismotectonic processes and focal zones on researched territory with required detailed elaboration.

The results of vibroseismic research within Altai–Sayan region, showing an initial stage of realized program, are presented below. The purpose of research is a detailed study of wave field from high-power vibrator on various distances for the following regime vibroseismic monitoring.

It is common knowledge that the method of vibroseismic sounding of observable objects, as distinct from passive methods, allows conducting active monitoring of objects to the point of steady tracing the stress-deformed state of some separations by a method of action on them of elastic vibrations. It is realized by a generation of seismic waves with high stability of emission (amplitude, phase, frequent spectrum, purposefulness). The seismic waves passed through the investigated object carry the information about happening modifications. The construction of time series of some investigated parameters, such as times of onsets of waves, time difference of onsets of waves, dynamic parameters (amplitudes, parameters of polarization), etc., determined by stress-deformed state of a medium, allows to realize uninterrupted control for rheologic characteristics of a medium.

The correct identification of target waves on which the monitoring is made, having various trajectories in the Earth's crust and various response to occurring modifications in a medium (refracted and reflected, P- and S-waves, etc.) is in this case a prime consideration.

Experimental vibroseismic research in Altai–Sayan region is followed from the middle 1980s. In different periods this work involves the leading organizations of the Siberian Branch: CC SB RAS, IGG SB RAS, NEMVE SB RAS, IM SB RAS and SDB AG SB RAS. The experiments performed over many years with various modifications of vibrators have shown high recurrence of emitted signals and large power of emission, permitting to carry out a monitoring of a wave field from vibrators on different distances [2, 3].

2. Field experiment

The most impressive data on study of a wave pattern from fixed vibrator are obtained on profiles Bystrovka–Aleysk (I–I) and Bystrovka–Maslyanino (II–II) (see Figure 1), intersecting inhomogeneous fold structures of Altai–Sayan region. The recording was carried out on different distances from fixed CVM-100 vibrator (centrifugal vibrator with amplitude of a force of 100 tons), mounted on an experimental polygon in area of the village

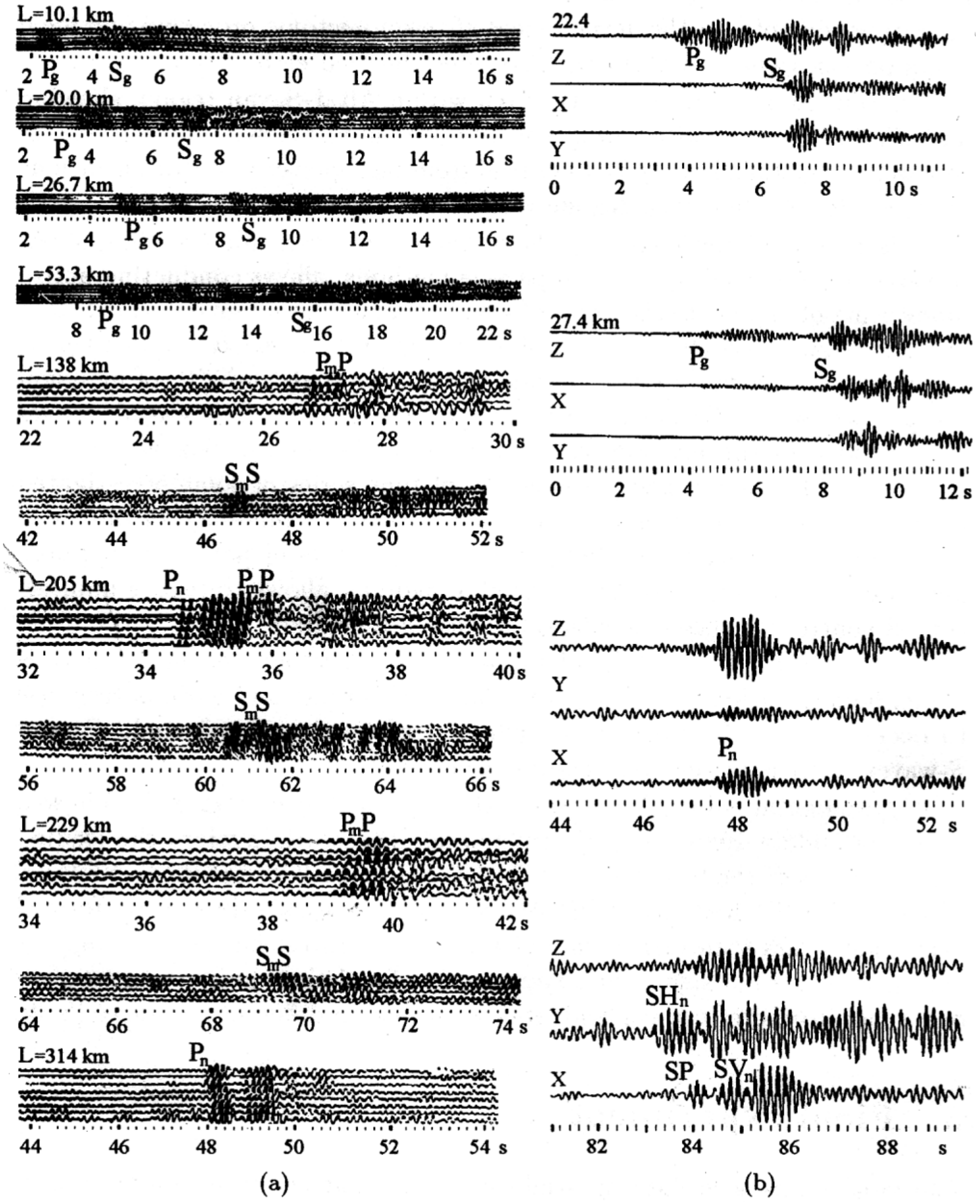

Figure 2. Examples of vibration records on different distances: (a) Records from vertical devices; (b) Three-component records

Bystrovka. On distances of 0–100 km on profiles I–I and II–II the recording was carried out with 5–10 km-interval; on distances in excess of 100 km the interval of recording made 20–40 km.

At observation on profiles I–I and II–II the frequency ranges of vibrator emission made 5.47–10 cps and 6.25–8.5 cps depending on the used unbalances with static moments 0.126 and 0.177, accordingly. The time of accumulation of signals varied according to distances of registration and used unbalances and made on the average 20–40 minutes on distances more than 100–150 km.

As equipment of registration the Russian multichannel digital registering equipment KARS, Beryoza, VIRS, Alpha–Geon and Japanese digital seismological server was used. On the profile Bystrovka–Aleysk (I–I) the registration in separate points was carried out on analog equipment "Taiga–Vibro", fitted with the block of digitization. The vertical groups of devices CB-5 (from nine detectors joint sequentially in groups) and three-component devices SK-1P were used for registration. The distance between groups of devices made 50–200 m.

As a result of registration on profiles I–I and II–II more than 60 correlograms with good signal/noise ratio on distances from 0 up to 314 km were obtained. The examples of correlograms for various distances are given in Figure 2.

3. Wave field and interpretation

The registered wave field from ZVM–100 vibrator on profiles I–I and II–II can be divided by convention on three areas: wave field on distances of 0–120 km, wave field on distances of 120–240 km and wave field on distances more than 300 km.

Distance of 0–120 km are an area of the sure registration of refracted P- and S-waves from boundaries in a top part of the Earth's crust.

Under the data of three-component records and records from vertical groups of devices (see Figure 2) we notice, that the field of longitudinal waves is reliable registered significantly on z-components, what can be conditioned by influence of low-velocity layer in a top part of a section. In the first onsets on distances of 0–130 km the three-four-phase waves are registered with apparent velocities on correlograms 6–7 km/s and visible frequencies 6–8 cps. TD curve on the first onsets of P-waves in a range of distances of 10–120 km on profiles I–I and II–II are good averaged by straight lines with values of apparent velocities 5.7–5.8 km/s (Figures 3–4).

The reduced times (velocity of a reduction 6.0 km/s) of P-waves on two profiles are closely related and vary from 0.2–0.4 s on basis of 10–20 km to 0.7–0.9 s on distances of 90–120 km. The absence of reversed and overtaking

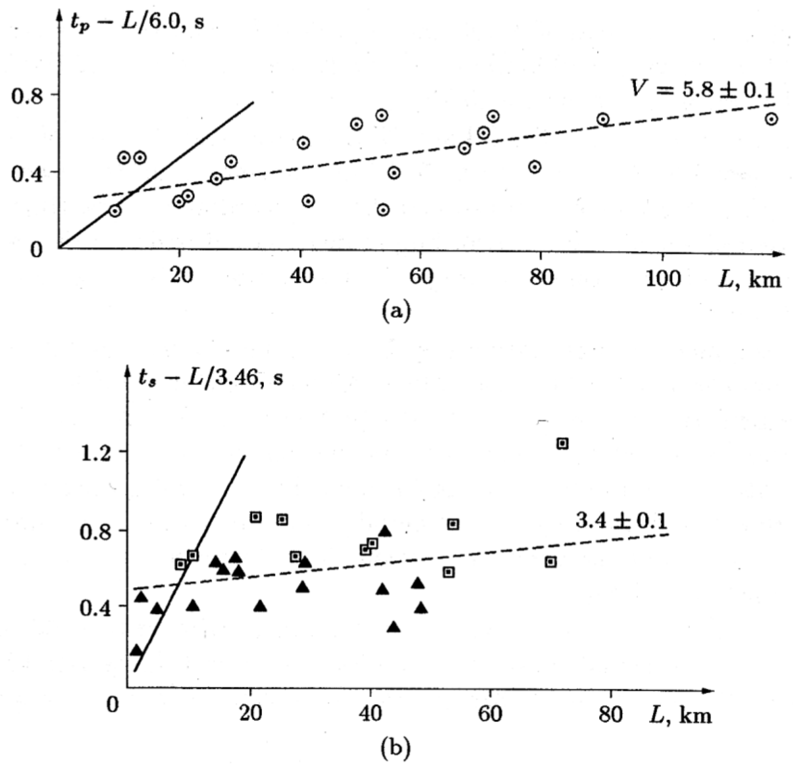

Figure 3. TD curves of refracted P- and S-waves (0–120 km)

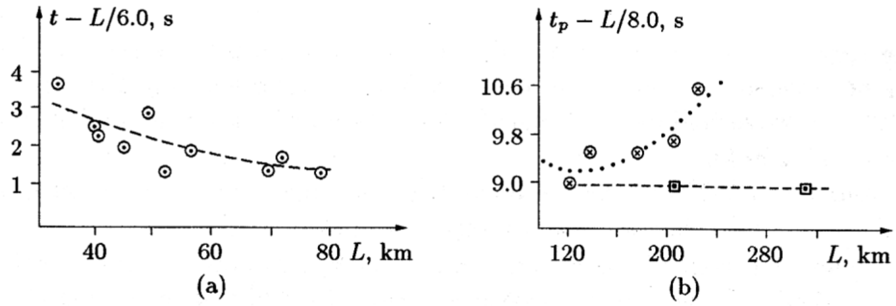

Figure 4.

(a) Reduced TD curve of P_cP-waves: experimental data of P_cP-waves from 100 tons vibrator and the theoretical TD curve of P_cP-waves for a model of a medium with parameters H=20 km, V=6.1 km/s;

(b) D curve of P_mP- and P_n-waves from the Moho surface: data of reflected and refracted waves from the Moho surface, accordingly (the theoretical TD curve of P_mP-waves for a model of a medium with the depth of the Moho surface 49 km and average velocity 6.4 km/s is shown in the figure by points)

TD curve does not allow only on vibroseismic data to determine uniquely a nature of waves in the first onsets, but using an information about velocities of seismic waves in a top part of section and correlating them with obtained TD curve, it is possible to make an assumption that the first onsets on seismograms generate waves, penetrating into original rocks on depth of weatherworn layer. The availability of a high velocity on small depth determines a tracing of this wave in the first onsets already on distances of 5–10 km. This wave may be considered as refracted on the boundary of the base (P_g).

In the following part of record after P_g-wave on vertical and three-component records (for the most part on z-devices) the multiphase groups of oscillations are picked up exceeding on intensity on frequent occasions P_g-waves. By analogy with DSS-data in this region [1] they are assigned to intracrustal reflected waves.

In a far part of seismograms on record times $t = 3t_p$ on vertical and horizontal devices on the profiles I–I and II–II the groups of oscillations are picked up, exceeding on intensity P_g-waves on z-components. On the relation of record times of these waves to P_g-wave, values of apparent velocities on seismograms and polarization of these groups of waves are assigned to transversal refracted waves from surface of basement (S_g). The values of apparent velocities of S-waves, obtained on average TD curve of these waves on the profiles I–I and II–II make accordingly 3.3 ± 0.1 and 3.4 ± 0.1 km/s. Average values of the ratio of velocities P- and S-waves and ratio of record times t_s/t_p on long distances (distances of 40–60 km, on which the influence of a top part on value of the time ratio of P- and S-waves becomes insignificant) are in close agreement (1.72–1.74), what confirms identification of these picked up P- and S-waves with the same surface of weatherworn crystalline rocks.

The analysis of good records of S-waves on x- and y-components shows that S-wave has x- and y-component, not divided on record times, what testifies about practical absence of anisotropy of velocities of seismic waves in a top part of crystalline crust. The given fact indirectly confirmed also by close values of velocities both P- and S-waves on a surface of the basement on practically orthogonal profiles I–I and II–II. The increase of intensity on z-components on record sites of S-waves on separate records is connected apparently with existence of converted SSP-wave.

In the following part of record after S_g-waves the intensive groups of oscillations are picked up, which by analogy to P-waves are assigned to crust reflection.

Distances of 120–240 km (see Figure 2). On these distances the intensity of refracted P- and S-waves from a surface of the basement falls, which are practically not picked up on correlograms. On the record sites of P- and S-waves only the groups of reflected P_mP- and S_mS-waves are picked up with confidence, identified by analogy with DSS works [1], as longitudinal and transversal reflected waves from a Moho surface. The groups of P_mP- and S_mS-waves are presented by multiphase records, the ratio of registration times of S-and P-waves makes up 1.74 ± 0.2. The value of effective velocity of longitudinal waves in the Earth's crust, determined on a fragment of TD curve P_mP-wave makes up 6.4 ± 0.1 km/s, and the value of depth of attitude of the Moho surface makes up 49 ± 2 km, what does not contradict to existing of geologo-geophysical understandings about a deep structure of area of concatenation of Siberian platform and Altai–Sayan fold zone. On some records ($L = 205$ km) in front of the intensive reflected wave (P_mP) the groups of oscillations are picked up, which can be identified as the refracted waves from Moho (P_n).

Distances of 300 km. The examples of vertical and three-component records for distances of 312 and 314 km are shown in Figure 2. On presented records one can see that on the site of registration of P-waves on three-component and vertical records the intensive group of oscillations is picked up with signal/noise ratio more than 3–4 times.

The approximate calculations on an average model of the Earth's crust of the research region allow classifying it as refracted longitudinal wave from a Moho surface (P_n). (The distance 314 km, calculated times P_n-waves for a model with parameters $H = 49$ km, $V = 6.4$ km/s, obtained on the profile Bystrovka–Aleysk, and values of boundary velocities on the Moho surface – 8.0–8.2 km/s, make 47.90–48.4 s, an experimental value of time of P_n-wave, defined on an experimental record, makes 48.15 s. The distance 312 km, calculated times for the above-listed parameters of a model make 47.6–48.2 s, experimental – 47.7 s.)

The integral values of apparent velocities, determined on P_n-wave on the distance of 314 km and initial point of P_mP-wave (see Figures 3–4) make up 8.0 ± 0.1 km/s, what does not contradict to common understandings about the properties of the Moho surface in this region. In a far part of seismograms on record times $t = (1.73–1.77)t_p$ the groups of intensive waves, identified on a ratio of times of registration of P- and S-waves and polarization as S_n-waves, are picked up. Because of a deficit of data it is impossible to identify confidently groups, picked up on x and z devices as SV_n-waves and groups, picked up on y devices as SH_n-waves (see Figure 2). The times of registration of these groups of waves vary in 1.2–1.4 s, what can point to the fact of existence of an anisotropy of elastic properties in the Earth's crust or along the Moho surface.

The integral values of velocities of S-wave on the Moho surface, determined on record data and data of S_nS-waves on distance of 138 km (in area of initial point of refracted transversal wave from the Moho surface) make up 4.55–4.75 km/s. The average values of velocities of P- and S-waves on the Moho surface make up 1.76 and effective Poisson's ratio – 0.26.

4. Results of research

As a result of the research a wave field from vibrating source of vertical force on distances from 0 to 314 km was studied in details. The following groups of waves are most confidently traced: on distances of 0–120 km – refracted longitudinal and transversal waves from surface of crystalline rocks (P_g- and S_g-waves); on distances of 120–240 km – reflected P- and S-waves from the Moho surface; on distances of more than 300 km – refracted P- and S-waves from the Moho surface.

Less confidently (irregular) on distances of 0–120 km the crust reflected P- and S-waves are registered, and on distances of 180–240 km the refracted P- and S-waves from the Moho surface are registered.

The marked groups of waves have various ways of transmission (P_g- and S_g-waves practically with small permeating) slide on a surface of crystalline rocks in a top part of the Earth's crust. P_mP- and S_mS-waves are propagated on all thickness of the Earth's crust and P_n- and S_n-waves (most part of way) are propagated along the Moho surface. The use of this information and data about areas in which the seismic events may occur (data on active fractures, information about focal of events, etc.) allows to select an optimum system of observation at performance of active vibroseismic monitoring. It is the author's opinion that at realization of monitoring, taking into account modern models of preparation of earthquakes, transversal refracted and reflected waves from the boundaries in the top and average part of the Earth's crust will become the most informative groups of waves. The availability of power SH-components from vibrator of vertical force will allow to study polarizing characteristics and elastic anisotropy of a medium, which immediately are connected with modification of microfissuring of a medium during preparation of seismic events.

The other essential result of fulfilled vibroseismic research in Altai–Sayan region is obtaining the new information about the elastic characteristics of P- and S-waves in the Earth's crust and upper mantle. The values of velocities of P- and S-waves in a top part of a crystalline crust of Altai–Sayan region make, accordingly, 5.7–5.8 and 3.3–3.4 km/s, for all the Earth's crust they are equal accordingly 6.4 ± 0.1 and 3.7 ± 0.1 km/s and for the Moho surface – 8.0 ± 0.1 and 4.55 ± 0.1 km/s. The average values of Poisson's ratio for these series make accordingly 0.245 ± 0.15, 0.25 ± 0.1 and 0.26 ± 0.1.

The fact of existence of anisotropy of elastic properties on the Moho surface and practical lack of anisotropy in a top part of Earth's crust was established.

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