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S-Wave Velocity Model for Several Regions of the Kamchatka Peninsula from the Cross Correlations of Ambient Seismic Noise

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Abstract—The data from the seismic networks of the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences are used for calculating the cross correlations of seismic noise for the stationary digital stations over 2013 and for radio telemetric stations (RTS) in the region of the Klyuchevskoy volcano over the period from January 1, 2009 to May 31, 2013. Four hundred and two correlations overall are calculated. The fundamental-mode group velocities of the Rayleigh waves are calculated in the periods ranging from 5 to 50 s. The calculations for the region of the Klyuchevskaya group of volcanoes are based on the RTS data and cover the periods from 2 to 8 s. The two-dimensional (2D) maps of group velocity distributions in different periods are constructed with the use of the algorithm of surface wave tomography (Barmin, 2001). The velocity sections for the selected Kamchatka regions are reconstructed by the dispersion curve inversion technique (Mordret, 2014). For each region, the structure of the Earth's crust and upper mantle down to a depth of 50 km was obtained.

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INTRODUCTION

The Kamchatka Peninsula is located in the interaction zone of three large lithospheric plates—Eurasian, North American, and Pacific—and two minor plates—Okhotsk and Beringia (Lander, 1994; Bogdanov, 1998; Avdeiko, 2002; Pedoja, 2006). It presents an example of the continental margin in the junction zone of the two largest Aleutian and Kuril–Kamchatka island arcs. This position implies a variety of complex geodynamical processes ongoing in this region, which is reflected in the high seismicity of Kamchatka

Seismic monitoring is one of the higher priority focuses of the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (KB GS RAS). It includes processing all the seismic data input to the KB GS RAS server in the real-time mode (Chebrov, 2013). Determining the reliable locations of earthquake sources is a primary task of seismological observations. The location quality of seismic events depends, inter alia, on the accuracy of the velocity model of the medium, which highlights the importance of the problem of reconstructing the velocity section.

Since the 1980s, studies of the velocity structure of the Earth have commonly used seismic tomography—a technique which employs the parameters of seismic waves (mainly travel times) for reconstructing the spatial distribution of mechanical properties (typically seismic *P*- and *S*-wave velocities) in the Earth's interior. Extensive studies with this technology also included the Kamchatka region. The first two-dimensional tomographic image in Kamchatka was obtained in 1987 in the study of the O-cone of the Klyuchevskoy volcano (Senyukov, 1987). The velocity section from the travel times of compressional waves was reconstructed in (Slavina, 1992; Gontovaya, 1995; Gorbatov, 1999). The *P*- and *S*-wave traveltime tomography yielded the velocity structure of the lithosphere within Central and East Kamchatka, including the territories of the bays (Gontovaya, 2003). The structure and distribution of velocity heterogeneities in the lithospheric block of East Kamchatka down to a depth of 200 km has been characterized in detail in (Nizkous, 2007). In (Gontovaya, 2007), the spatial structure of the lithosphere of Central and East Kamchatka was identified by comparing the data of the geological and geophysical studies of Kamchatka with the velocity model of the upper mantle. The tomographic methods were not

† Deceased.

only applied in the studies based on body waves but also in the works considering surface waves. The use of the surface wave dispersion enabled the authors of (Shapiro, 2000; Levin, 2002; 2005; Gordeev, 2009; Droznina, 2012) to obtain the *S*-wave velocity section for the Kamchatka Peninsula and neighboring tectonic structures. The crustal velocity structure beneath the Klyuchevskaya group of volcanoes from the arrival times of *P*- and *S*-waves from volcanic earthquakes localized within the studied volume was reconstructed by different seismic tomography methods and from different initial data. The first reconstruction was conducted in (Lees, 2007) based on the seismological observations of 1981–1994. The more detailed results based on measurements over 2000–2010 were achieved in (Stepanova, 2004; Gontovaya, 2004; Nizkous, 2005a; 2005b; Koulakov, 2011; 2013).

It is worth noting that with the existing seismicity distribution and locations of seismic stations in Kamchatka, a high-resolution determination of the crustal structure by the traditional methods is only possible for certain separate areas of the considered region (Gontovaya, 2007).

In the past decade, an alternative tomography method which was proposed in the works on acoustics (Weaver, 2001a) and seismology (Shapiro, 2004; 2005) has been developed. Instead of the signals from the earthquakes or artificial seismic sources, this method considers the wave fields reconstructed from the cross correlations of seismic noise. The method relies on the idea that the cross correlation function of the noise obtained by averaging over a long time interval, in the ideal case converges to Green's function (Weaver, 2001b; Snieder, 2004; Roux, 2005; Gouédard, 2008). The cross correlations of ambient noise are calculated from the continuous seismic records by a pair of stations; each station can be converted into a virtual source radiating a wave field which is represented by the correlation functions of seismic noise. The full correspondence between the cross correlations and Green's functions can only be achieved when the correlated noise is completely random and its sources are uniformly distributed in space (Campillo, 2006). In reality, the sources of seismic noise are largely concentrated on the surface of the Earth; therefore, the surface seismic waves (fundamental modes of the Rayleigh and Love waves) are most easily reconstructed from the ambient-noise cross correlations (Campillo, 2011). The distribution of the sources of seismic noise on the Earth's surface is also not quite uniform (Stehly, 2006; Landès, 2010) and in this case, the surface wave amplitudes cannot be estimated from the ambient noise correlations. At the same time, in the case of a weakly heterogeneous distribution of the noise sources, the cross correlations can be used for measuring the arrival times of seismic waves (Garnier, 2009). As a result, the cross correlations of ambient seismic noise are most frequently used for measuring the surface wave traveltimes (dispersion curves) and their subsequent inversion for the velocity structure of the crust and upper mantle. This approach is referred to as the ambient noise surface wave tomography (ANSWT) (Ritzwoller, 2011).

In our work, the ANSWT method was applied to the continuous records of the vertical components by the seismic stations in Kamchatka. Using the obtained cross correlations we managed to measure the group velocities of the fundamental modes of the Rayleigh waves at the periods of 2–50 s based on which we obtained the models of *S*-wave velocity distributions down to a depth of 50 km. The stations' layout precluded us from achieving uniformly high resolution for the all the regions of the Kamchatka Peninsula. Therefore, as the final results we present the average velocity sections for several regions: South Kamchatka, the East volcanic belt, the Sredinnyi Range, and the Klyuchevskaya group of volcanoes.

DATA

The network of permanent seismic stations of KB GS RAS includes the network of stationary digital seismic stations (DSSs), the network of radio telemetric seismic stations (RTSSs), and the network of strong motion seismic stations (SMSs). In 2013, the Kamchatka seismic network incorporated 71 sites of seismic signal recording which are equipped with the communication channels transferring data in real time (Chebrov, 2013; *Sil'nye*.., 2014).

Seismic channels of stationary stations include the Guralp CMG 3TB velocimeters (UK) (http://www.guralp.com/products) with a frequency band of recorded seismic signals 0.0083–40 Hz; CMG 6T (0.033–40 Hz), and CMG 6TD sensors with a built-in data recorder (Mishatkin, 2011). Seismic signals are digitally recorded by the instruments developed in 2002–2005 at KB GS RAS, namely, a stationary digital seismic station (SDSS) (Chebrov, 2006) and data recorders GSR-24 (GeoSIG, Switzerland) and DM 24 (Guralp, UK) (Mishatkin, 2011).

The signals from radio telemetric stations are transferred through a radio channel with the use of FM-FM modulation to data acquisition centers in Petropavlovsk-Kamchatskii, Kozyrevsk, and Klyuchi, either directly or through a transponder. All the stations are equipped with a three-component set of short-period SM3KV velocimeters recording the seismic signals in frequency bands of 0.7–20 Hz. Some stations are provided with upgraded SM3KV velocimeters—SM3vch (4–20 Hz). The equipment of RTSS was developed in 1974–1982 for operatively monitoring active volcanoes (Gavrilov, 1987).

The system for the acquisition, processing, storage, and visualization of seismological data relies on the capabilities of the enterprise-wide network of KBGS RAS. The data acquisition and transfer system is organized based on Internet channels, RadioEthernet technological communication networks, and HughesNet and Idirect technologies' VSAT satellite networks.

The network uses specialized servers for buffering the data flows from the network stations. The specialized archival seismic data servers which are based on two six-level RAID arrays and located in the regional informational and processing center Petropavlovsk are used as the main file storage repository. The data are stored in the form of daily files for each station (Chebrov, 2010).

In this study, we used continuous data from 22 stationary stations with a sampling frequency of 100 Hz and from 19 radio telemetric stations with a sampling frequency of 128 Hz. The locations of the stations are shown in Fig. 1.

DATA PREPROCESSING. CALCULATION AND RESULTS OF CROSS CORRELATIONS

In this work, we used seismic records of the vertical components from the DSS and RTSS networks in the region of the Klyuchevskaya group of volcanoes (Fig. 1). The original records by these two network types were digitized with sampling frequencies of 100 and 128 Hz, respectively. For reducing the volume of the processed data, we rarefied the records to 8 Hz (RTSS) and 10 Hz (DSS). After this, the data were organized into segments with a length of 24 h. In accordance with the procedure suggested in (Bensen, 2007), the seismograms were subjected to spectral whitening in the interval between 0.01 and 3 Hz and binarized. For the DSS data, the cross correlations were calculated between all station pairs for each day of 2013. For the DTSSs, the calculations were carried out for the period from January 1, 2009 to May 31, 2013. All the daily correlation functions for each station pair were summarized. The correlations were calculated for 402 station pairs (231 for DSSs and 171 for RTSSs). The resulting waveforms are shown in Fig. 2. The Rayleigh waves are clearly tracked for interstation distances up to 300–400 km. For measuring the group velocities (described in the next section) we used the symmetrical components of the correlation functions which are calculated as an average of the positive and negative parts.

MEASURING THE GROUP VELOCITIES

For the Rayleigh surface waves identified in the records of the correlation functions for each station pair, we measured the group velocities. The group-velocity dispersion curves of the Rayleigh wave fundamental modes were calculated by the time-frequency analysis method (Levshin, 1986). In the Russian language literature on the subject, the analysis of the signal based on time-frequency representation is referred to as SVAN (Lander, 1973). This method for the mathematical processing of seismic records consists in filtering the input signal by a set of relatively narrow-band filters, which differ by the central frequency, and representing the signal amplitude and phase by a function of two variables—time and central frequency of the filter. With the use of SVAN it is possible to solve the key problems of surface wave processing (Levshin, 1986). For measuring the Rayleigh wave group velocities, we used the Matlab program presented in (Mordret, 2014). Figure 3 shows the dispersion curve obtained for the KBG–KIR path (the distance between the stations is 151 km). The color background of the plot corresponds to the SVAN diagram where the maximal amplitudes are shown in intense red. The black dots mark the relative local maxima of the diagram. The dispersion curve that was determined automatically is marked by white circles around certain points. The black line is the five-order polynomial approximation of the dispersion curve.

The station pairs for calculating the dispersion curves were selected by the criteria suggested in (Bensen, 2007). Distances shorter than two wavelengths were not considered, and only the measurements that were obtained with the high signal-to-noise ratio (estimated based on the SVAN analysis) were stored. Figure 4 shows the layout of the stations and the interstation rays for which the measurements were carried out. The group velocities of the fundamental mode Rayleigh waves were calculated at the periods ranging from 5 to 50 s. The rays are shown in different colors depending on the group velocity values obtained in a given period. The example is shown for periods of 15 and 30 s which correspond to the depths of approximately 15 and 30 km.

The calculations for the region of the Klyuchevskaya group of volcanoes were carried out for periods ranging from 2 to 8 s based on the data from the RTS and DS stations. The locations of RTS stations and the rays linking them are illustrated in Fig. 5. The number of the group velocity measurements obtained at each period is indicated in the table.

2D GROUP VELOCITY TOMOGRAPHY

In the course of preprocessing the data for tomography, we constructed all the obtained dispersion curves and determined the average one. After this, we rejected the curves the values of which fell beyond the two-sigma vicinity of the average curve. The selected (remaining) dispersion curves were then used for constructing the two-dimensional (2D) maps of group velocity distributions in different periods. This was done by the ANSW tomography algorithm (Barmin, 2001) implemented in the Matlab language (Mordret et al., 2014). The numerical grid for Kamchatka had a step of 1 degree in longitude and 0.5 degrees in latitude. The maps were calculated for ten periods between 5 to 50 s. The grid parameters for the Klyuchevskaya group of volcanoes were refined to 0.5 degrees in longitude and 0.25 degrees in latitude; the maps were obtained for seven periods between 2 and 8 s. The

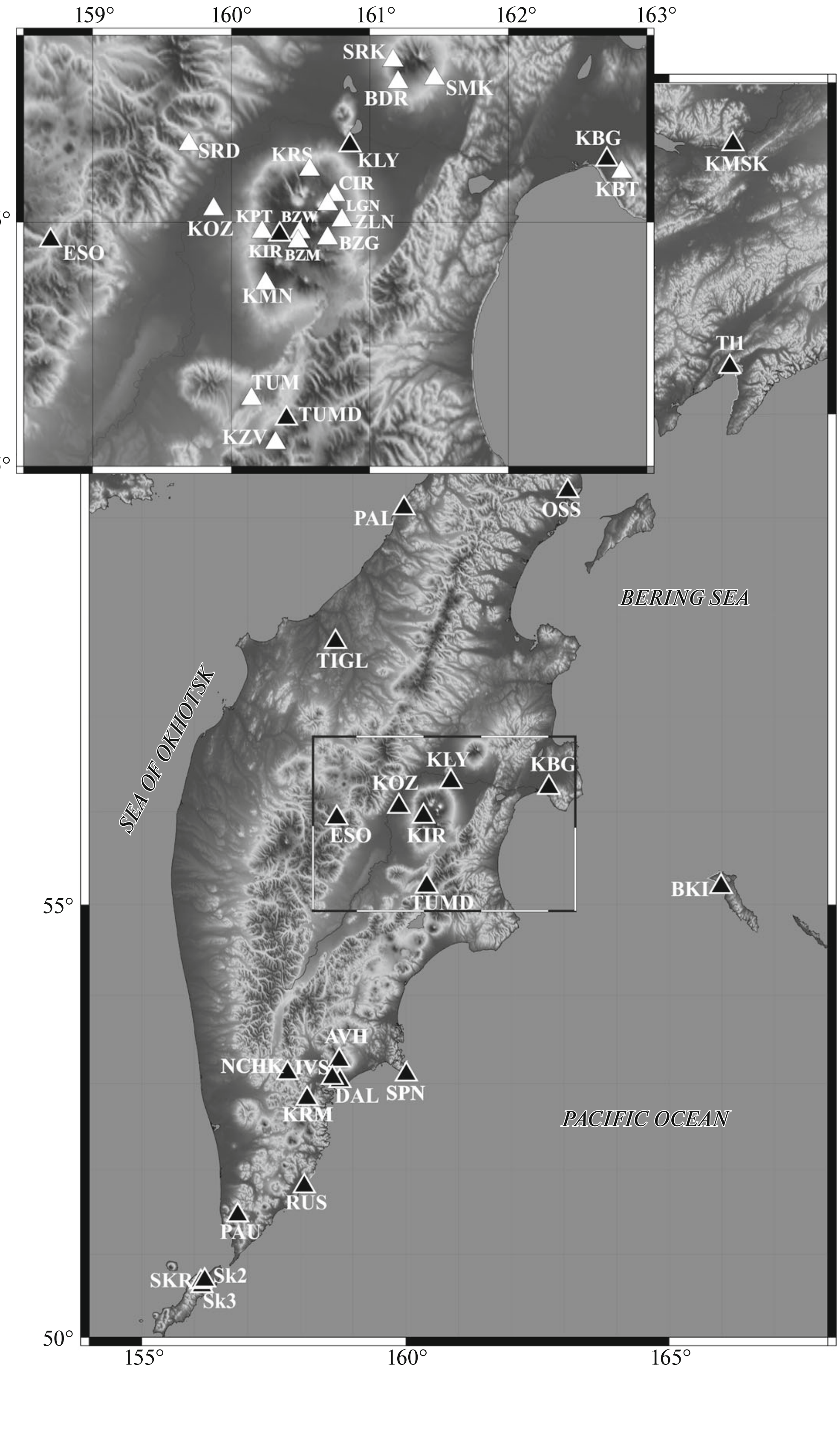

Fig. 1. Map of Kamchatka and seismic stations whose data were used in this work. Inset shows region of Klyuchevskaya group of volcanoes. Black and white triangles indicate broadband stations and short-period stations, respectively.

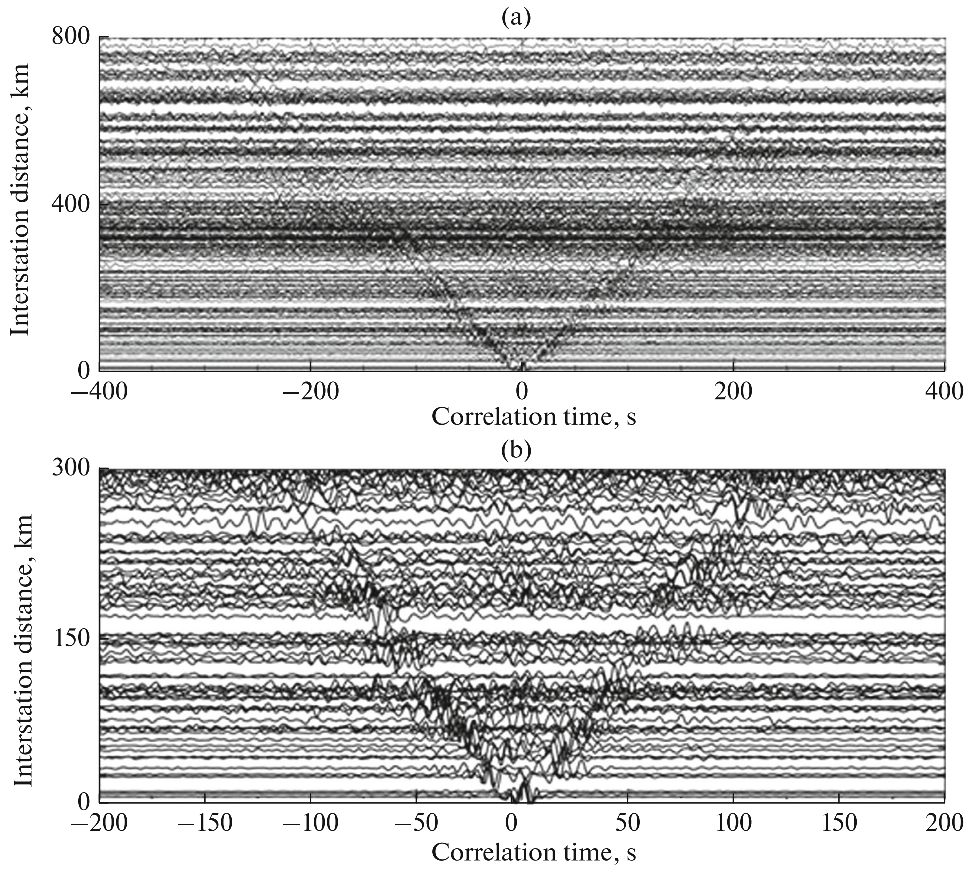

Fig. 2. Example of cross correlations between different stations of Kamchatka regional network: (a) correlations for all probable stations spaced apart from each other by at most 800 km; (b) correlations for stations located within 300 km from each other.

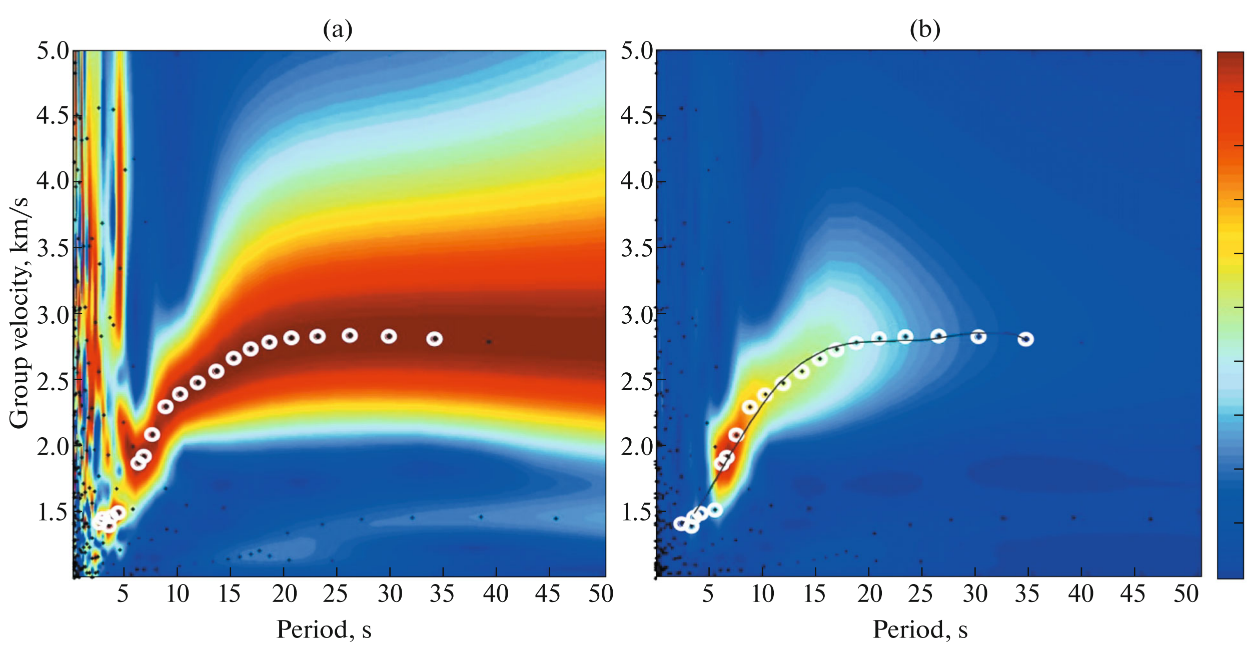

Fig. 3. Rayleigh wave group velocity dispersion curve for KBG-KIR ray path: (a) signal envelope normalized to period, i.e., maximal amplitude of signal is selected at each period; (b) curve without normalization, i.e., absolute maximum in amplitude of signal in given range of periods.

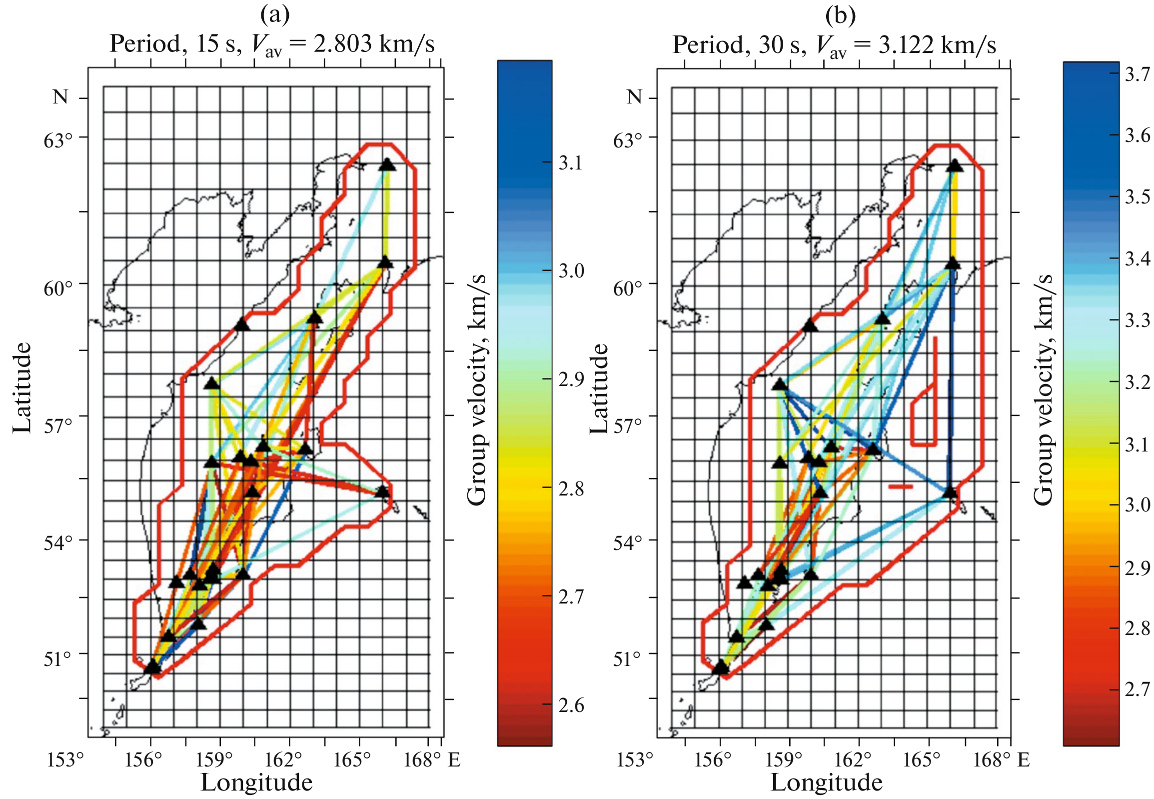

Fig. 4. Group velocities and rays covering Kamchatka Peninsula. Black triangles denote stationary DSSs. Right: color scale of group velocity. Results of calculations at period of (a) 15 s and (b) 30 s.

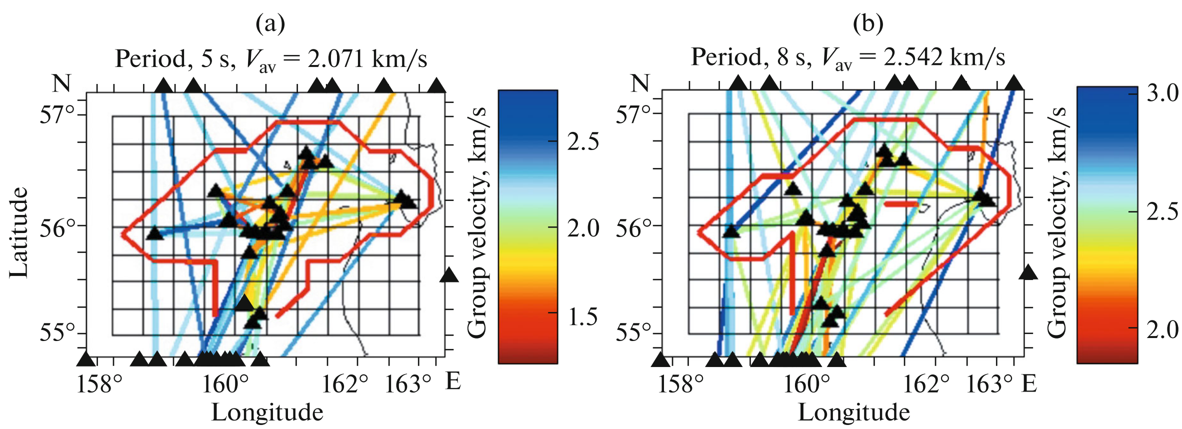

Fig. 5. Group velocities and rays covering region of Klyuchevskaya group of volcanoes. Black triangles indicate RTS stations. Right: color scale of group velocities. Results are calculated for period of (a) 5 s and (b) 8 s.

examples of the group velocity maps for the different periods are shown in Figs. 6 and 7.

For each map of the group velocity distribution (Figs. 6, 7), the mean velocity value and the parameter VarRed are indicated. The latter shows the reduction in the variance between the travel time values calculated from the initial model and obtained for the final model. In all cases, this parameter is >50% indicating

Number of group velocities measurements in each period

Period, s	2	3	4	5	6	7	8	10	15	20	25	30	35	40	45	50
Number of measurements	35	102	134	146	140	129	116	110	115	105	93	80	66	57	52	40

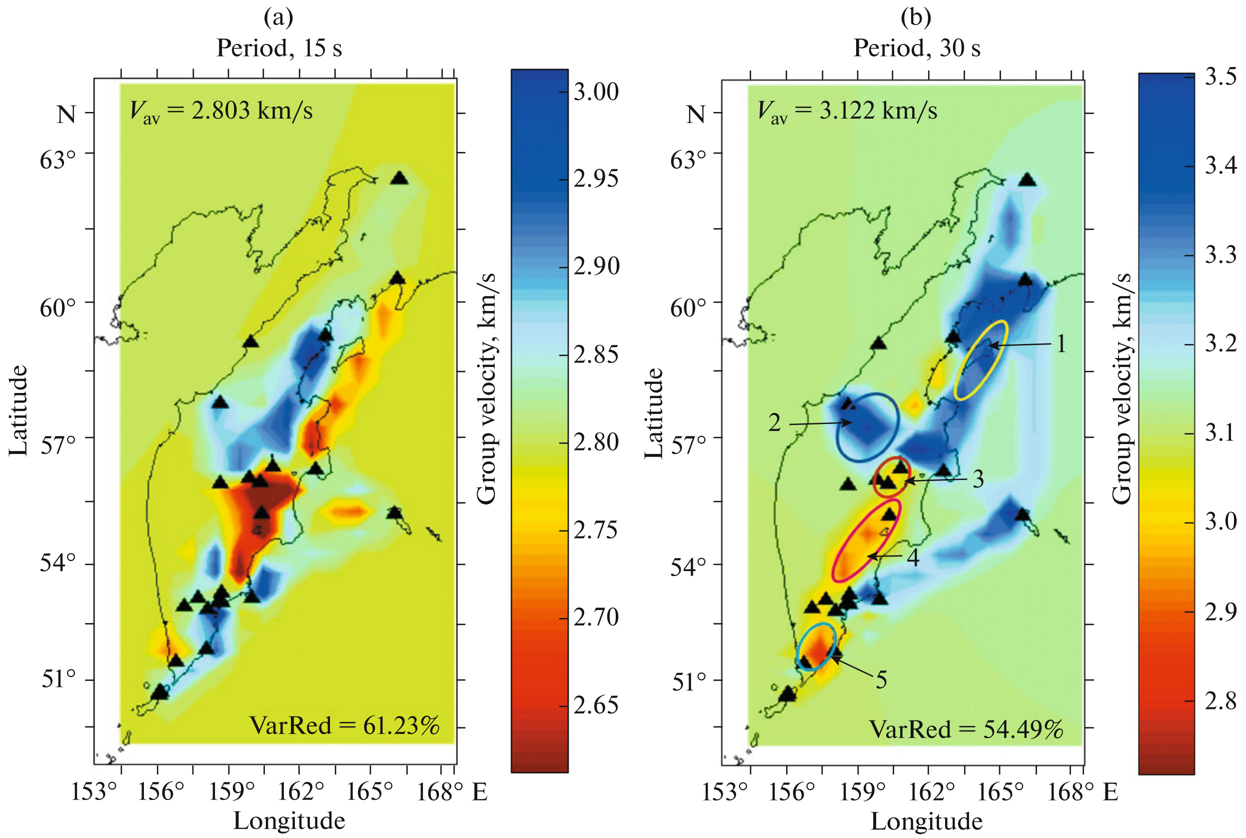

Fig. 6. Rayleigh wave group velocity map for Kamchatka Peninsula. Black triangles denote stationary DSSs. Right: color scale of group velocity. Background of plot corresponds to color of average velocity values. Results of calculations for period of (a) 15 s; (b) 30 s. Colored ellipses with numbers show regions selected for constructing depth sections.

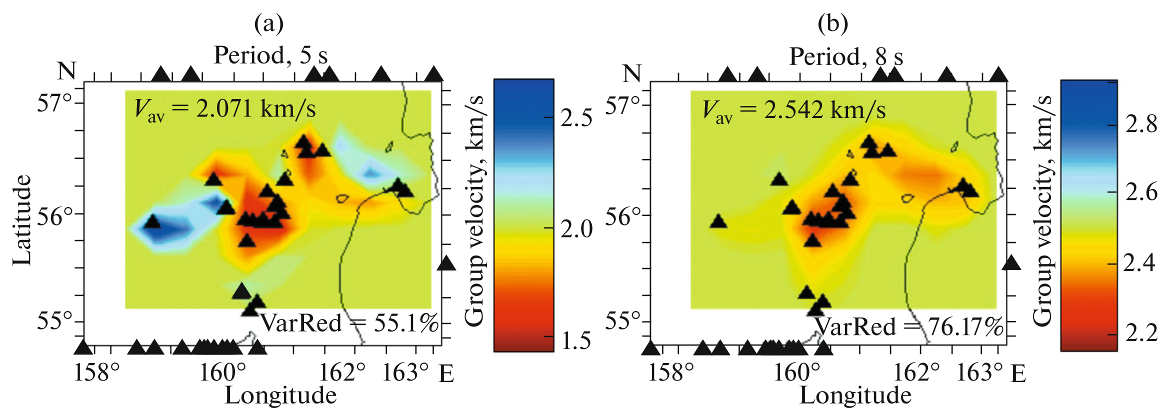

Fig. 7. Rayleigh wave group velocity map for region of Klyuchevskaya group of volcanoes. Black triangles denote stationary DSSs. Right: color scale of group velocity. Background of plot corresponds to color of average velocity values. Results of calculations for period (a) 5 s; (b) 8 s.

that the obtained set of the group velocity measurements can only be accounted for by the models of the medium that include horizontal heterogeneity.

CONSTRUCTING THE DEPTH SECTIONS

The one-dimensional inverse problem on reconstructing the velocity section from the Rayleigh-wave group-velocity dispersion curve was solved by the Neighborhood Algorithm (Sambridge, 1999), a version of the Monte Carlo method. The algorithm is described in detail in (Mordret, 2014).

For this modeling, we selected separate regions which are shown by the colored ellipses in Fig. 6: 1, Karaginskii Bay; 2, the northern part of the Sredinnyi Ridge; 3, the Klyuchevsakaya group of volcanoes; 4, the Eastern Ridge; and 5, the southern part of the Kamchatka Peninsula. We selected the dispersion curves that were computed for the rays passing in the corresponding regions, and for each selected region we calculated the mean curve. The velocity section was reconstructed in the horizontally uniform model of the medium. The initial model had six layers, three in the crust and three in the mantle. The layer thicknesses and velocities were specified according to the model for Kamchatka obtained in the previous works (Shapiro, 2000; Levin, 2002). In the upper mantle, we used the results of the *P*-wave apparent velocity measurements (Slavina, 1974; Fedotov, 1976) converted into *S*-wave velocities by the formula $Vp/Vs = 1.73$. For the region of the Klyuchevskaya group of volcanoes, we added two layers in the surface part of the model which correspond to the volcanic deposits. The thicknesses and velocities for this volcanic region were specified according to the velocity model that has been used at KB GS RAS since 1999 to the present time for determining the parameters of earthquakes from the Northern group of volcanoes (Senyukov, 2004). The *S*-wave velocities determined for the periods from 2 to 8 s based on the RTS stations data were complemented by the velocity values for periods ranging from 10 to 50 s obtained from the data of the DS stations at the nearest point. In the course of the inversion, the *S*-wave velocities and the depths of the layers were varied, whereas the Vp/Vs was fixed and assumed to be 1.73. For each region, the inversion yielded 2000 models fitting the observations. These models are shown by the black lines on the left in Fig. 8. The white line shows the model that is close to the average. Thus, the average *S*-wave velocities in each layer and the layers' top and bottom depths were found. The velocity models for five selected regions and the average dispersion curves from which these models were constructed are shown in Fig. 9.

DISCUSSION AND CONCLUSIONS

Based on the ambient seismic noise correlations, we managed to determine the Rayleigh wave group velocity dispersion curves between numerous pairs of seismic stations. The obtained group velocity values appreciably vary between different station pairs, and the seismic tomography based on these data shows that the structure of the crust and upper mantle of the Kamchatka Peninsula is strongly inhomogeneous. In the present work, we limited ourselves to obtaining the averaged models (Fig. 9a) for the five structural regions shown in Fig. 6b.

In four of the five regions, the obtained crustal thickness is ~30–35 km, which corresponds to the middle crust of the continental type and is close to the estimates in the average models for the Kamchatka crust published in the previous works (Kuzin, 1974; Shapiro, 2000). A significantly thinned crust (~25 km) is revealed beneath region 1 (Karaginskii Bay). This crustal thinning can probably be associated with the relatively smooth transition from a continental to an oceanic structure in this region, where active subduction has not occurred over the past few Ma (Alexeiev, 2006).

The *S*-wave velocity in the upper mantle in most regions is found to vary within 4.2–4.3 km/s. This relatively low value, compared to the Earth's average structure models, can partly be accounted for by the fact that the results were obtained from the Rayleigh waves alone, without using the Love waves. With this approach, the probable radial anisotropy in the upper mantle (Ekström, 1998) is disregarded which, in turn, can lead to the underestimated mean velocities of the *S*-waves. At the same time, the low *S*-wave velocities associated with high mantle temperatures are typical of the back-arc regions in the subduction zones. The significantly lower velocity in the upper mantle beneath the Klyuchevskaya group of volcanoes can be related to the presence of a magma chamber.

The lowest velocity in the upper and middle crust is revealed beneath region 4 (Eastern volcanic belt). This tectonically youngest part of the Kamchatka Peninsula was formed by the accretion of the Kronotskaya island arc which has occurred since Late Eocene (Alexeiev, 2006; Avdeiko, 2007). In this case, the observed difference in seismic velocities and, correspondingly, in the crustal structure can be due to the structural distinction associated with tectonics.

The results presented in this paper show the possibility in principle to use the method of ambient noise surface wave seismic tomography for studying the crustal and upper mantle structure in the regions with a complicated tectonic structure such as Kamchatka. At the same time, the layout of the operating permanent seismic stations precludes us from reconstructing the structural models with a sufficiently high and uniform resolution for the entire Kamchatka Peninsula. In the future, this resolution could be increased by installing new permanent seismic stations or by conducting large-scale field experiments with temporary stations.

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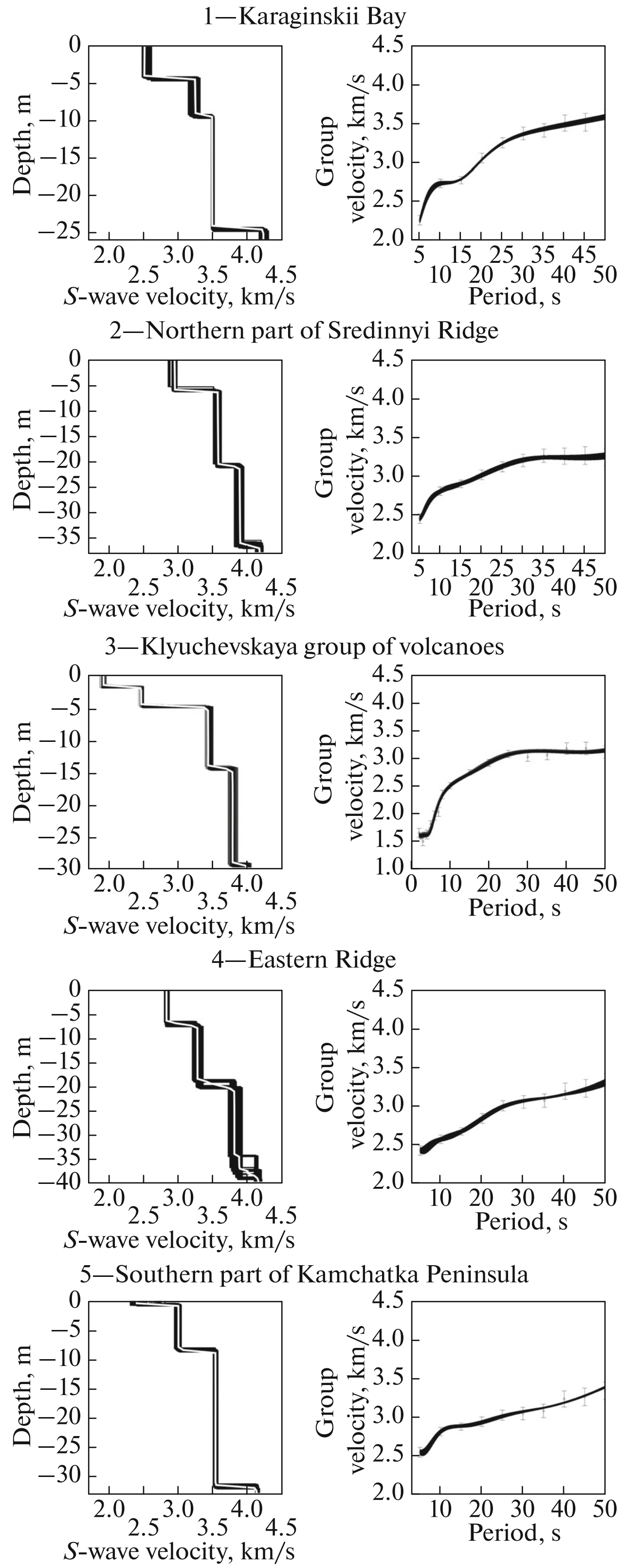

Fig. 8. Left: *S*-wave velocity model for different regions of Kamchatka Peninsula. 2000 models fitting observations are shown in black. White line shows model that is close to average. Right: dispersion curves corresponding to obtained 2000 models (black lines); mean dispersion curve based on which models have been reconstructed is shown by error bars.

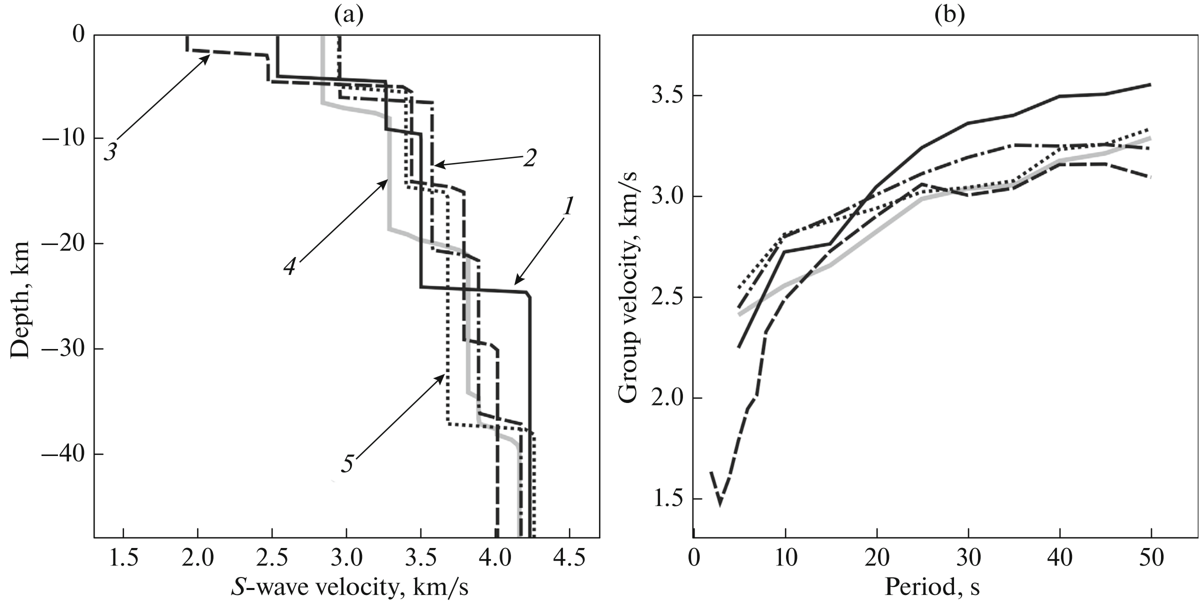

Fig. 9. *S*-wave velocity sections for different regions of Kamchatka Peninsula. (a) Numeral corresponds to region shown by ellipse in Fig. 6; (b) mean dispersion curves.

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