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The 1995 Neftegorsk Earthquake: Tomography of the Source Zone

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Abstract—The Neftegorsk earthquake of May 27, 1995, which was the most destructive earthquake within the present boundaries of Russia, was studied by the International Epicentral Expedition, which gathered unique data on the surface rupture and on its aftershocks. In the present study, based on these data and employing the method of local seismic tomography, a 3-D velocity structure is obtained, and aftershock hypocenters are relocated. It is shown that the earthquake source (fault plane) does not unambiguously correlate with variations in the velocity field. However, areas of lower velocities correspond to source ends, as was noted in other similar papers. In several cross sections, the source area correlates with a bench of velocity contours. Overall, the area under study indicates a high degree of velocity inhomogeneity.

INTRODUCTION

The Neftegorsk earthquake of May 27, 1995, was the most destructive earthquake within the present territory of Russia ($M_S = 7.6$, $M_W = 7.1$). It produced tremors of an 8–9 intensity in the territory of the small town of Neftegorsk, which led to widespread destruction and human casualties (about 2000). Immediately after the earthquake, the International Epicentral Expedition was organized including specialists from the Joint Institute of Physics of the Earth (JIPE), Russian Academy of Sciences (RAS); the Geological Institute, RAS; Far East Division of RAS; and the Research Center for Earthquake Prediction, Hokkaido University, Japan. The earthquake, whose source coincided with the Piltoun fault, produced a surface rupture 40 km long. The fault was mainly a right-lateral slip with a maximum slip amplitude of 8 m [Kozhurin and Strel'tsov, 1995; Arefiev *et al.*, 2000]. Numerous aftershocks were recorded during one and a half months of joint field observations [Aref'ev *et al.*, 1995]. A rather high density of seismic stations ensured high accuracy of hypocenter locations. These observations provided a basis for the study of the 3-D structure of P wave velocities and local tomography of the earthquake source zone.

The Neftegorsk earthquake significantly exceeded the existing level of seismic hazard estimates for this region and made it necessary to revise the seismic zoning map for Sakhalin. Although the source zone is located near a large tectonic structure (the Sakhalin–Hokkaido fault), the rupture occurred on the less significant Piltoun fault.

The source modeling employing the widespread method of body wave inversion demonstrated a good fit with observations and revealed additional features at the initial stage of rupturing in the source [Arefiev *et al.*, 2000].

Seismic tomography methods have been intensely developed in recent years due to the progress in computer technologies and numerical methods. In this study, we employ a new method of local seismic tomography that enables the determination of seismic velocities on a given 3-D grid and, simultaneously, the relocation of earthquake hypocenters [Thurber, 1983; Eberhart-Phillips, 1986].

The knowledge of the 3-D velocity structure in the source zone of a strong earthquake and an accurate localization of hypocenters of its aftershocks allow the refinement of the geometry of the source and its position in real tectonic structures.

METHOD

The experimental stage of this work included the study of the earthquake source zone, namely, organizing and conducting field epicentral observations, data gathering, and their initial processing [Aref'ev, 1994; Aref'ev *et al.*, 1995]. The interpretation stage employed the method of local seismic tomography [Thurber, 1983; Eberhart-Phillips, 1986, 1990].

Epicentral seismological observations have been conducted by JIPE RAS since at least the Ashkhabad earthquake of 1948. Despite obvious technological difficulties of the prompt organization of observations under conditions of destroyed towns, the epicentral observations over a limited period provide a huge amount of data that can be compared with years of ordinary regional observations and thereby improve the quality and reliability of the earthquake source analysis. Moreover, large volumes of high-quality seismological information collected in the epicentral zone of a strong earthquake allow one to apply methods initially developed for other cases, for example, seismic tomography.

Methods of seismic tomography are various and numerous, and their complete review is not the purpose of this study. We chose the method of local tomography proposed by Thurber [1983] and developed later by Eberhart-Phillips [1986, 1990] and other researchers [e.g., Dorbath *et al.*, 1996]. This method provides simultaneous 3-D inversion of seismic wave velocities and reevaluation of the coordinates (relocation) of earthquake hypocenters. The velocity is parametrized at the nodes of a 3-D grid whose sizes are determined by the quantity and quality of initial data and are chosen so as to yield the number of ray paths sufficient for 3-D mapping of velocity. The method allows the use of a nonuniform grid. The velocity at each point along the ray and the partial derivatives of travel times with respect to hypocenter parameters (source coordinates and earthquake time) and velocity are calculated by linear interpolation between the eight closest grid points. Thus, the resulting values vary monotonously rather than in a steplike manner, as is usually obtained in models using refracted waves or block-type parametrization. The monotonous, rather than steplike, variation in velocity is preferable in studies of regions with a complex geological structure, because, for example, block modeling can be completely unacceptable with reference to real velocity heterogeneities. Velocities obtained at grid nodes can easily be represented in the form of fields or contour maps, which simplifies their comparison with other results.

The approach proposed by Thurber [1983] uses the least travel time arc for the approximation of the ray path. This is an effective technique but it sets constraints on the application of the method. At large distances, refracted waves can be first arrivals, and in this case, a circular arc is a poor approximation and overestimates the path length. In practice, this means the absolute applicability of the method at epicentral distances of about 20–45 km and, accordingly, in areas with linear sizes of about 100 km [Eberhart-Phillips, 1986], which is sufficient for studying epicentral areas of strong earthquakes.

INITIAL DATA AND CALCULATIONS

The source of the Neftegorsk earthquake was located in the northern part of the Sakhalin Island. According to the global plate tectonics, this region coincides with the boundary either between the North American and Eurasian plates [DeMets *et al.*, 1990] or between the Eurasian and Okhotsk plates, if a more fractured structure of tectonic plates is accepted [Seno, 1995]. Figure 1 shows the location of the source zone of the Neftegorsk earthquake within Northern Sakhalin. The surface rupture is mapped using the data by Kozhurin and Strel'tsov [1995] and coincides with that given by Arefiev *et al.* [2000]. The surface topography is plotted using the 30-s database (GTOPO, USGS, EROS Data Center) available on Internet. The correlation of separate tectonic structures with the topography is well seen. Figure 1 also shows the aftershock epicenters (368 events, circles) analyzed later and stations (triangles). The epicenter locations were determined at the first stage of data processing, when the aftershock catalog was compiled [Aref'ev *et al.*, 1995].

An important parameter in Thurber's method [Thurber, 1983] of calculations is the damping parameter. We estimated it with an empirical method analogous to that proposed by Eberhart-Phillips [1986] and set it to be equal to 10. We calculated P wave velocities.

The area under study was covered with a 3-D grid; its projection onto the surface is shown in Fig. 2. The figure also shows the epicenters of relocated aftershocks and the lines along which the model cross sections are constructed. Note that the choice of the specific grid for the area of interest was somewhat arbitrary and was intended to obtain the maximum possible resolution on a reasonable level of accuracy and the most detailed velocity structure compatible with the available initial data. The grid was chosen after a series of trial calculations. The initial data being nonuniform throughout the area studied, the resulting grid was also nonuniform. In order to better fit the surface rupture and its orientation, the grid was rotated through 16° eastward from the direction to the north. The origin of the grid coordinates (52.85° N, 142.895° E) coincides with the midpoint of the surface rupture, and the ordinate axis is oriented along it. The grid parameters were as follows: –38, –27, –17, –9, –4, 0, 4, 8, 12, 17, 23, 31, and 40 km along the vertical (nearly E–W orientation); –35, –26, –19, –13, –8, –4, 0, 4, 9, and 15 km along the horizontal (nearly N–S orientation); and depth levels of 0, 2.5, 5, 7.5, 10, and 12.5 km. Note that, since data were insufficient on some depth levels, a resolution parameter was additionally mapped for each layer. These maps are not presented in this paper. In accordance with these maps, velocity values were plotted only in those areas of the territory under study, where the resolution was 0.1 or better. An example of cross sections of the resolution parameter illustrating the selection of spatial regions in which the calculation results are presented is given in Fig. 5b.

Maps of longitudinal wave velocities in each layer are shown in Fig. 3. The epicenters of earthquakes located in the corresponding layer are also plotted. Since the fault in the earthquake source is nearly vertical, the same projection of the surface rupture is shown for all layers. Figure 4 gives a 3-D representation of the same cross sections with velocity contours plotted at a 0.5-km/s interval. Note that the area surrounding the surface rupture is representatively shown only for the layers at 5, 7.5, 10, and partly at 12.5 km. Statistics for other layers are insufficient.

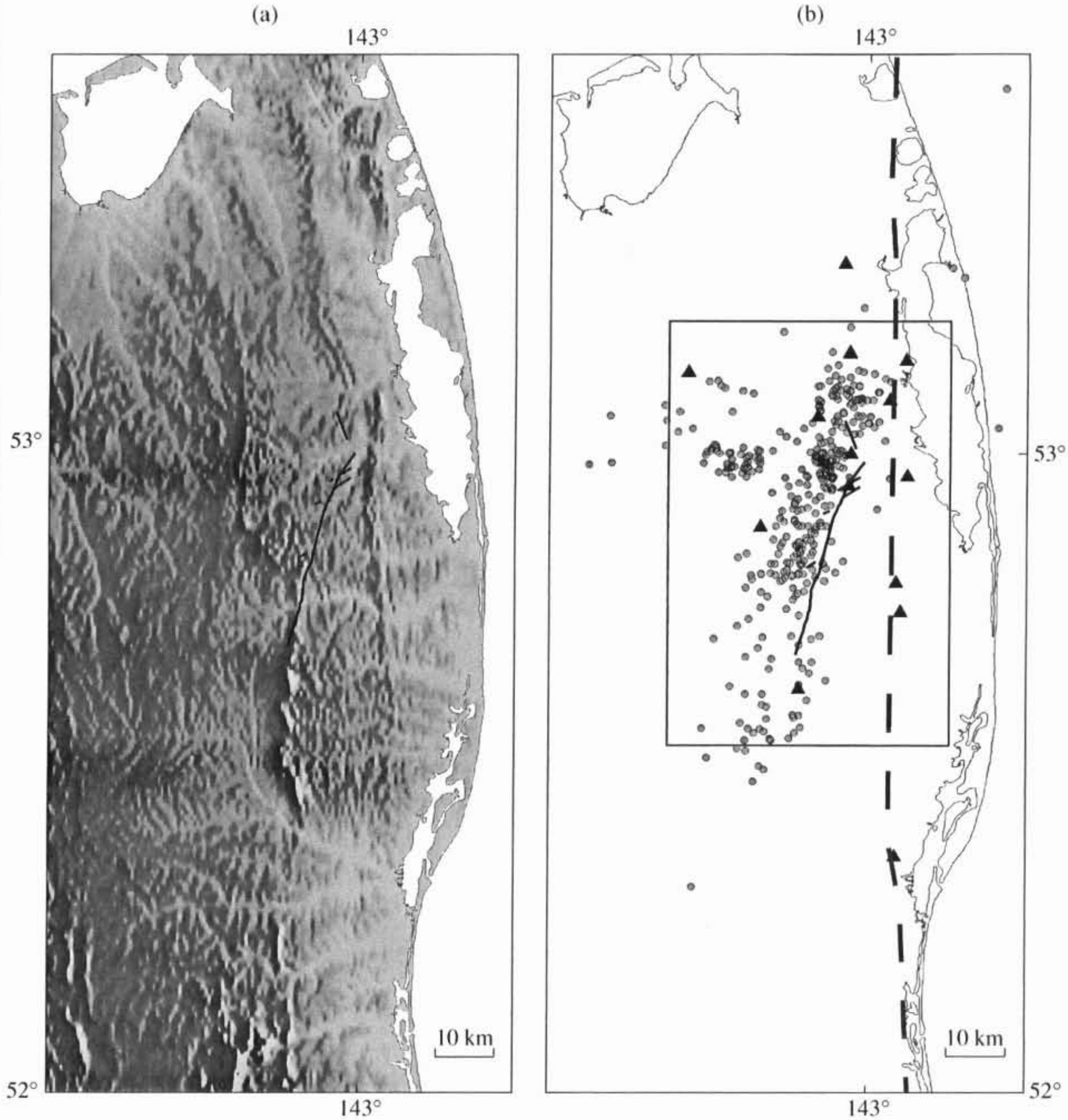

Fig. 1. Source zone of the Neftegorsk earthquake: (a) topography; (b) aftershock epicenters (circles), seismic stations (triangles), and the Sakhalin–Hokkaido fault (broken line). The solid bold line is the projection of the surface rupture.

The cross sections along the lines shown in Fig. 2 and the histogram of the depth distribution of number of hypocenters are presented in Fig. 5a. In cross sections A, B, C, and D, the zero value on the abscissa axis coincides with the surface rupture. In cross section E, the projection of the surface rupture is shown as a bold line. The abscissas from –17 to 17 km encompass the main part of the surface rupture (without its northern branch). Figure 5b shows the cross sections of the resolution parameter, corresponding to those in Fig. 5a. The lighter areas were chosen for the representation of results. Beyond these areas, the calculated velocities are unreliable.

Figure 6 presents the map showing the relocated aftershock epicenters and the E–W cross section and compares them with previous determinations (HYPO71, [Aref'ev *et al.*, 1995]).

DISCUSSION OF RESULTS

The Neftegorsk earthquake significantly exceeded the expected level of the maximum energy in Northern

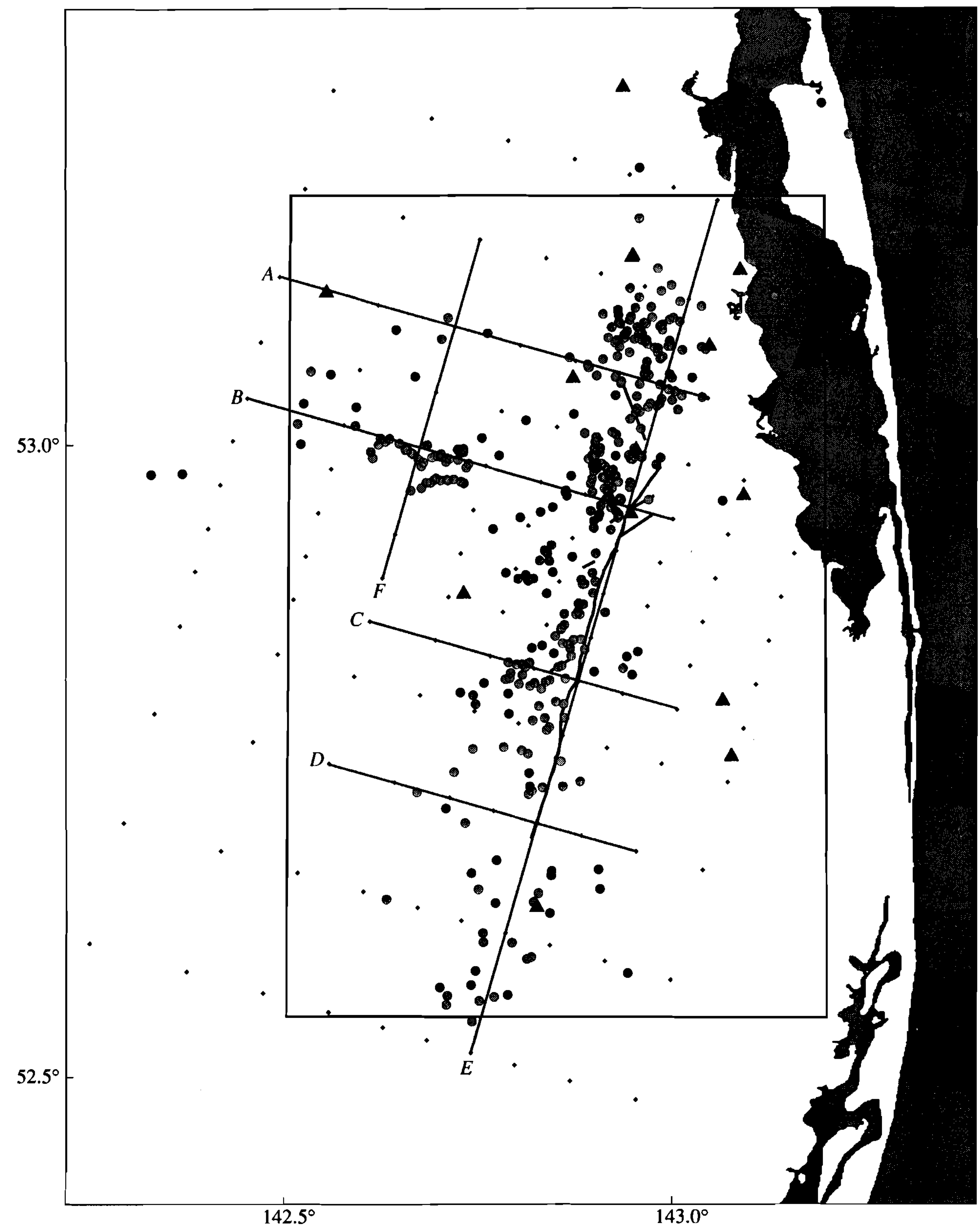

Fig. 2. The area under study, grid points, lines of cross sections, and relocated epicenters of aftershocks. For notation, see Fig. 1.

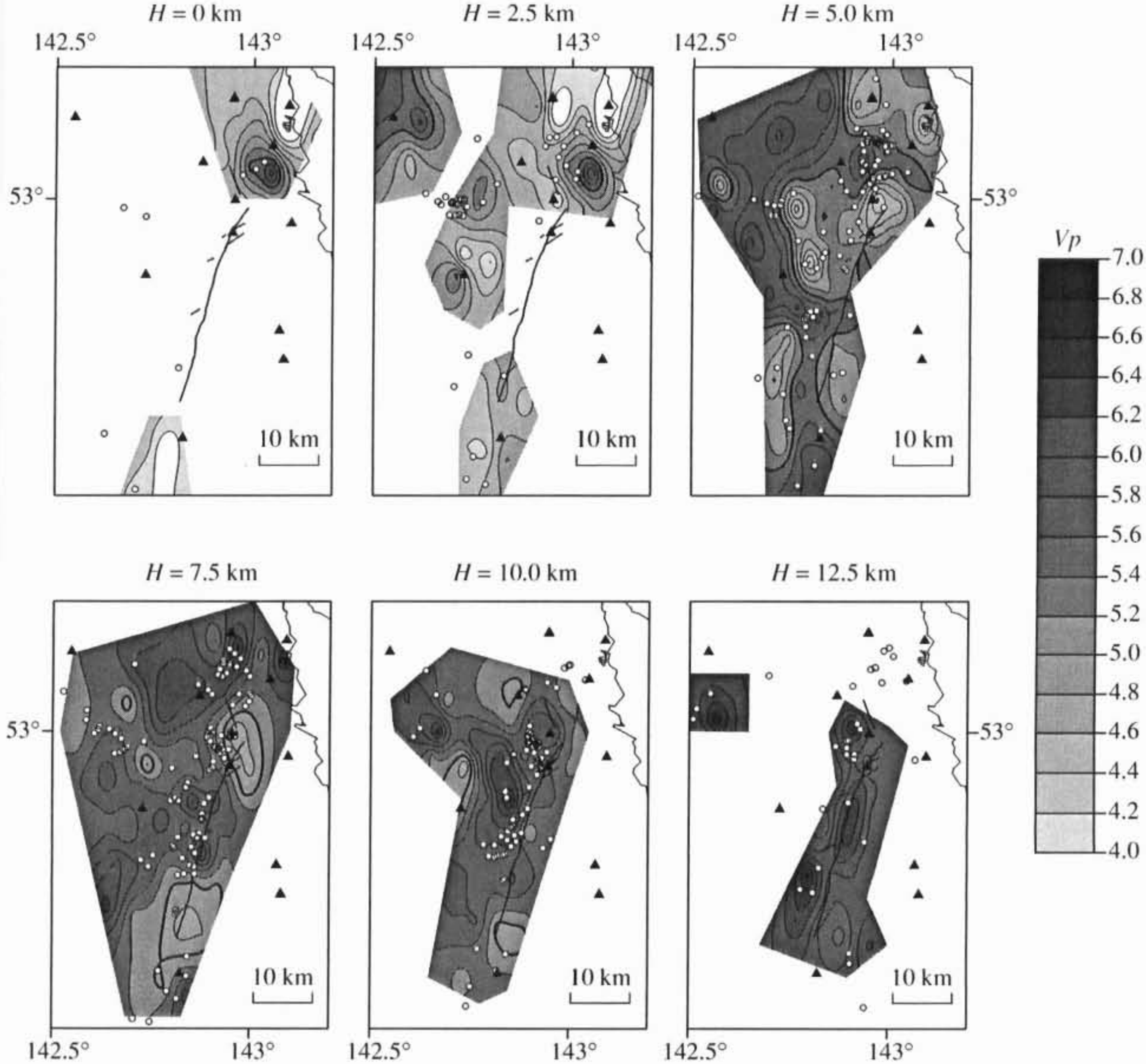

Fig. 3. Contour maps of longitudinal wave velocities for various layers. Each map shows earthquakes whose hypocenters are within the pertinent layer. For notation, see Fig. 1.

Sakhalin. However, the rupture produced by the earthquake was associated not with the main tectonic structure of the region (the Sakhalin–Hokkaido fault) but with the secondary Piltoun fault; the rupture occurred nearly all along its length. At first glance, the Neftegorsk earthquake seemed to be a fairly simple seismic event (clearly visible and well-mapped surface rupture consistent with nearly pure right-lateral slip and a good CMT fit). However, more detailed analysis revealed that this earthquake was a complicated multistage process with a nontrivial geometry [Arefiev *et al.*, 2000]. The amount of available observation data was sufficient for the local seismic tomography of the epicentral zone along with the revision of its aftershock hypocenter positions. The histogram of depth distribution of the relocated aftershocks is more uniform than that derived from the HYPO71 data [Arefiev *et al.*, 2000], which indirectly indicates a higher quality of the relocated catalog. The structure of the longitudinal wave velocities in the epicentral zone, as inferred from the aftershock data reveals a very complicated, mosaic pattern (typical in similar cases). The relocated aftershocks show noticeable individual divergences in hypocenter locations; however, the main features of their spatial distribution coincide with those discovered in our previous papers: the cloud traces well the surface rupture but is not compact; the overwhelming majority of aftershocks are located west of the rupture; and the cluster unrelated to the surface rupture is clearly recognized. Arefiev *et al.* [2000] associate this cluster with the first

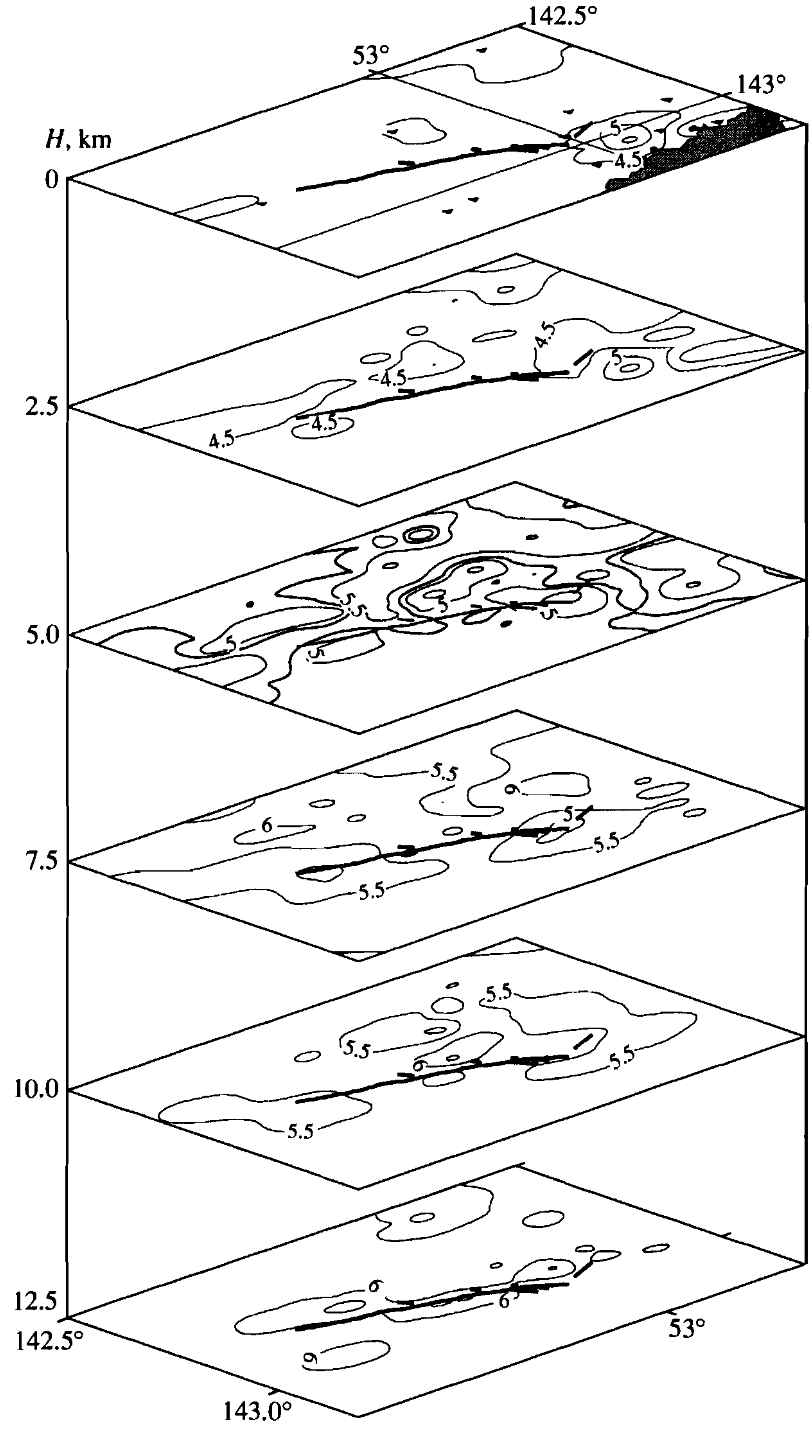

Fig. 4. 3-D representation of the contour maps of longitudinal wave velocities. For notation, see Fig. 1.

stage of the complicated rupturing process in the earthquake source.

The published data characterize the area under study as follows. The earthquake source region is oil and gas bearing and is seismically rather well studied. There are numerous wells, but their depths do not exceed 2–2.5 km and are not relevant to our study. Upper Cretaceous sediments have velocities ranging from 5.0 to 6.0 km/s. According to data of deep seismic sounding, the surface of the consolidated crust dips toward Sakhalin Island from a depth of 4 to 7.5 km and has a boundary velocity of 6.1–6.4 km/s [Crustal Structure ..., 1964]. In our case, such velocities are beyond reliable determination. Argentov *et al.* [1992], using the method of refracted waves, determined the seismic cross section

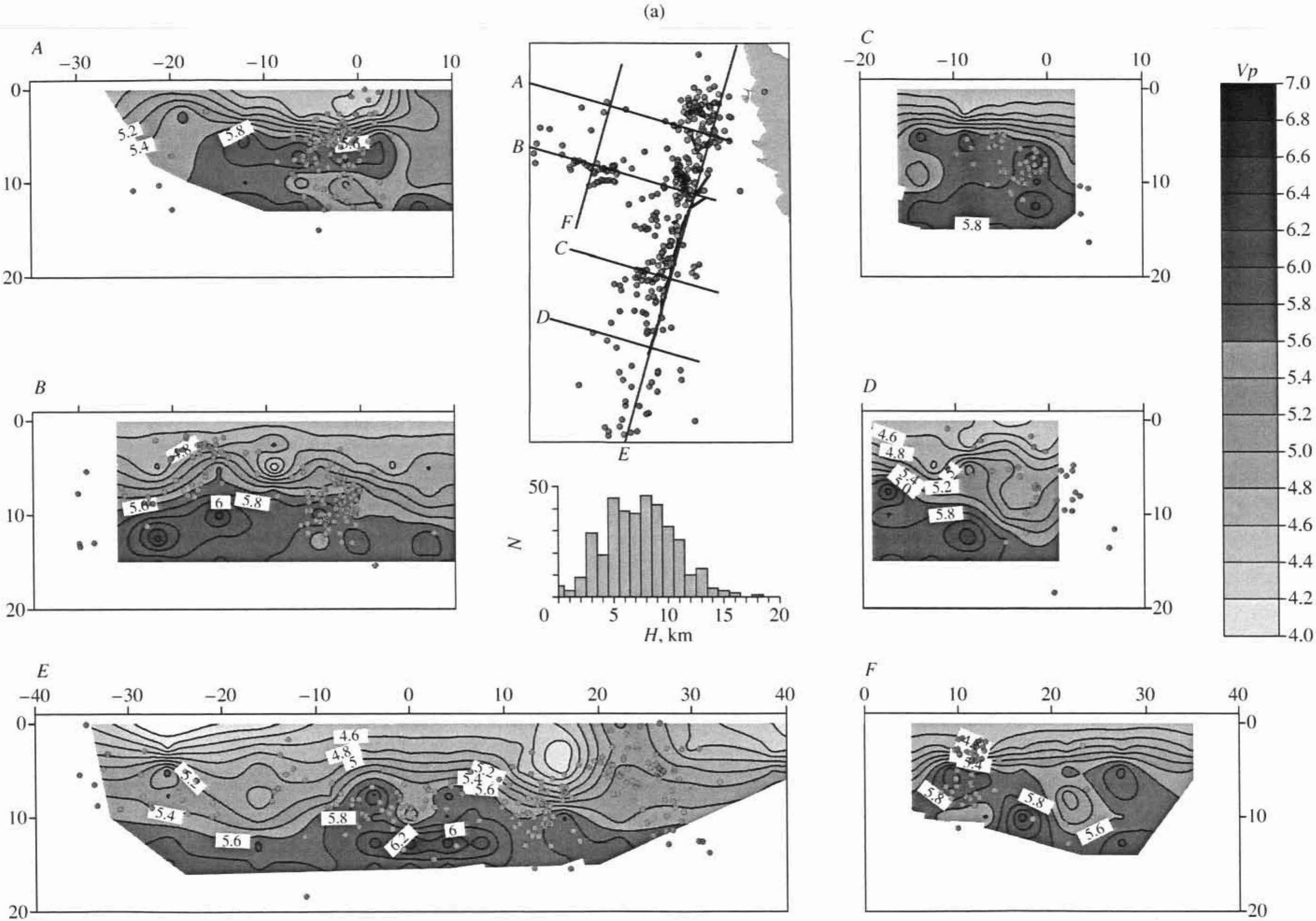

Fig. 5. (a) The cross sections along the lines shown and the depth distribution histogram of the number of earthquakes: for notation, see Fig. 1. (b) The cross sections of the resolution parameter (see text for explanations).

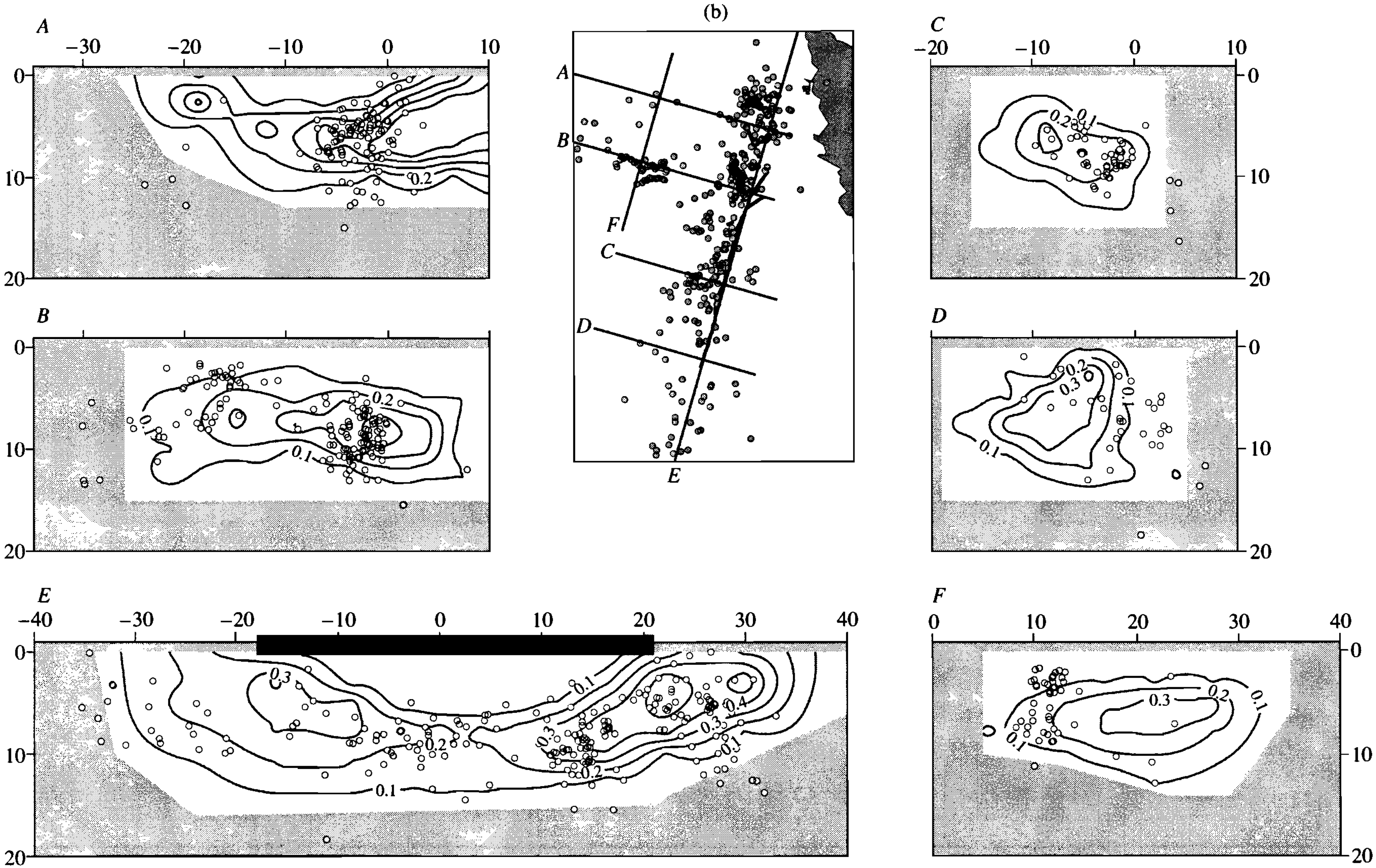

Fig. 5. (Contd.)

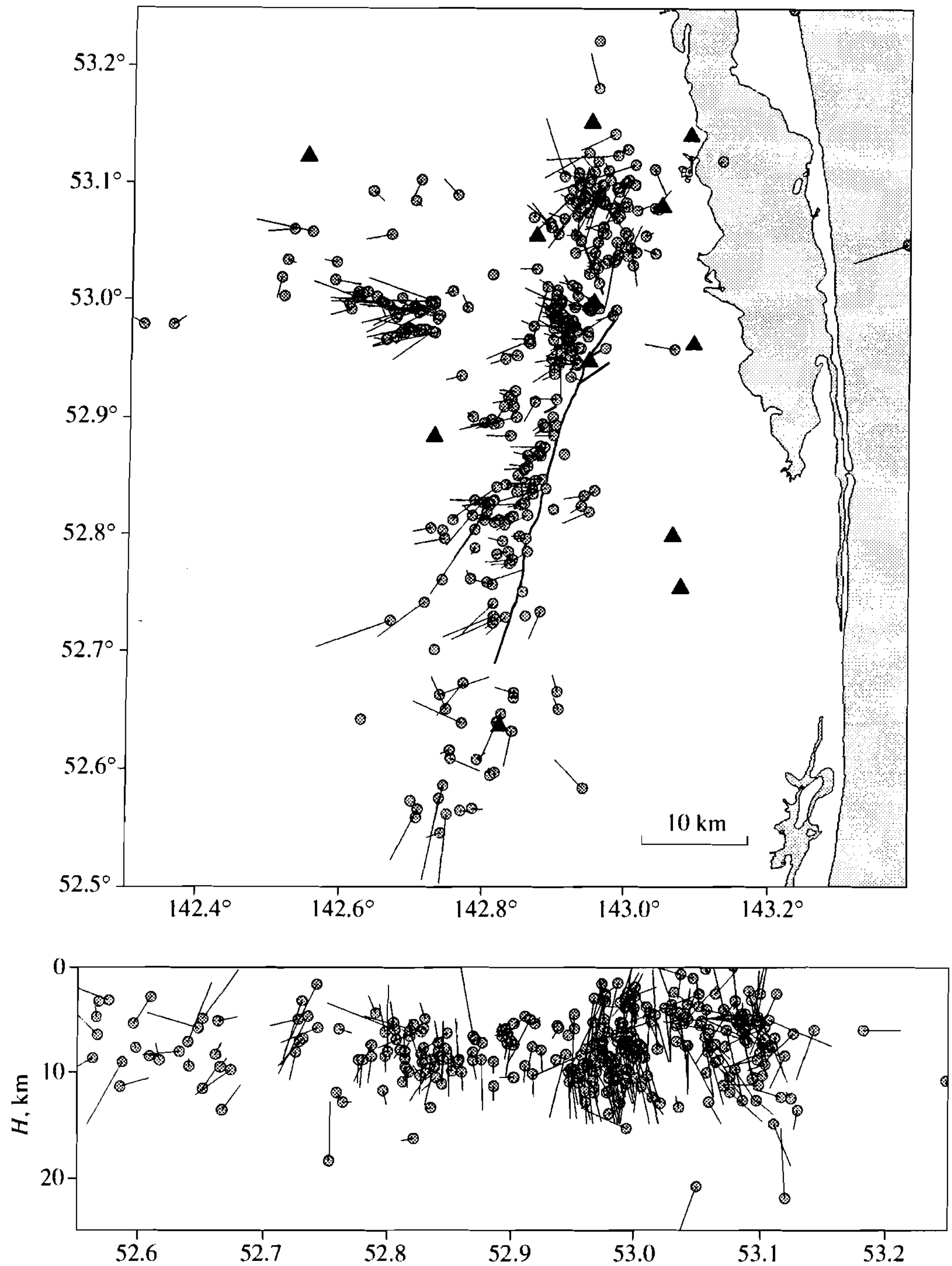

Fig. 6. Relocated (circles) and initial (opposite ends of bars) hypocenters: (a) epicenter map; (b) E–W cross section. For notation, see Fig. 1.

along the profile running along the western coast of the island. Here, the thickness of sedimentary deposits is 7.5–10 km, and the sedimentary cover consists of two layers: the upper high-gradient, strongly stratified layer 3.5–4 km thick and the lower low-gradient layer. A velocity of 4.8–5.2 km/s is evidence for the transition from normal sedimentary to siliceous rocks.

In the cross sections of Fig. 5, we marked the 5.2-km/s contour, which coincides, in our opinion, with the boundary mentioned above. Note that, according to our data, this boundary is somewhat deeper as compared with the results of previous papers. Unfortunately, our data are inadequate for the reliable localization of the crystalline basement boundary in the velocity field.

We also note that the velocity field does not clearly resolve the seismic source fault. This result seems to be somewhat strange and, at first glance, indicates shortcomings of the method. However, to the best of our knowledge, similar studies of source zones of strong earthquakes using similar methods also gave no constraints on the source rupture position in the velocity field. This fact can, in particular, indicate that the source rupture giving rise to the earthquake source can rapidly heal and become indistinguishable from surrounding rocks in the field of seismic wave velocities. As regards various areas of the source fault, a few interesting moments, noted also by other researchers, are noteworthy. For example, the ends of the crack (fault) correlate with areas of relatively low velocities (Figs. 3 to 5). Moreover, a bench in velocity contours is clearly seen in the vicinity of the fault (Fig. 5). Overall, the 3-D velocity pattern is rather inhomogeneous. The *P* wave velocities differ considerably in various areas of the study region at the same depths. Our study failed to trace the basement boundary, but the other boundary noted in [Argentov *et al.*, 1992], was found to occur, on average, at greater depths.

CONCLUSIONS

1. The source zone of the Neftegorsk earthquake was studied using the local seismic tomography method. A 3-D model of *P* wave velocities is obtained, and aftershock hypocenters are relocated.

2. It is shown that the earthquake source (fault plane) does not correlate unambiguously with variations in the velocity field; however, it is noteworthy that the lower-velocity regions correlate with the source ends, and the source zone correlates with a bench in velocity contours in some cross sections.

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