Structure and Peculiarities of the Seismic Regime in the Source Zone of the Takoe Earthquake on September 1, 2001 (MW 5.2)

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Abstract—The Takoe earthquake (MW 5.2) occurred between two en-echelon segments of the active Aprelovskii fault on September 1, 2001, and was accompanied by an earthquake swarm, which was successfully recorded by a local network of digital seismic stations located on the southern part of Sakhalin Island. Modern methods were applied to relocate the parameters of the sources for the earthquake swarm event and significantly specify their spatial distribution and relations to the structural–geological features of the complex system of interacting faults. New data on the correlation between the source mechanism and the modern geodynamic setting in the southern part of Sakhalin were obtained.

Key words: earthquake swarm, seismic activation, hypocenter, active Aprelovskii fault, Southern Sakhalin.

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INTRODUCTION

In order to understand the causes and conditions for the occurrence of destructive earthquakes and to develop reliable methods for their forecasting and objective algorithms for quantitative estimation of the seismic hazard, it is required to correlate the seismic activity with the deep structures and processes occurring in the Earth’s crust. A necessary condition for the reliable distinguishing of this correlation is the exact spatial localization of the earthquake sources. Before 2001, a detailed investigation of such type was hardly possible in Sakhalin because of the sparse regional seismic network, which yielded a mean error in determining the earthquake hypocenters of 10–15 km. The appearance of a local digital seismic network in the southern part of Sakhalin opened principally new possibilities for detailed studying of the spatiotemporal distribution of the weak earthquake sources in the Earth’s crust.

Detailed investigation of the seismic activity recently found with paleoseismological methods in the large active fault zones (Aprelovskii, West Sakhalin, Garomaiskii, Pil’tunskii, and others) of Sakhalin [1] is of the greatest practical interest. The manifestation of present-day activity in the Aprelovskii fault can be exemplified by the Takoe earthquake swarm recorded by the local digital seismic network on July–September 2001 (Fig. 1).

The objective of this study, based on the modern algorithms for processing digital seismological data, is the large-scale relocation of the main parameters of the Takoe earthquake sources to define more exactly the source position and to distinguish the relation of the swarm activity with the deep structure and seismic tectonics of the region.

DOUBLE DIFFERENCE METHOD

In most cases, the parameters of earthquake hypocenters are determined using the travel time inversion method [9] widely accepted in seismic observations around the world. This method is underlain by the assumption that the difference between the real and inferred location of the earthquake zone is small.

Fig. 1. Location map of seismic stations. (1) Seismic stations used in the calculations; (2) Temporal network of stations; (3) Takoe earthquake on September 1, 2001 (MW 5.2).
enough to express the residual difference as a linear correction function for the true location of the hypocenter.

The calculated arrival time $t_k^i$ (of P- or S-waves) from the $i$th earthquake for seismic station $k$ can be written as

$$t_k^i = \tau^i + T_k^i,$$  \hspace{1cm} (1)

where $\tau$ is the time of the source of the $i$th event and $T_k^i$ is the arrival time as a function of the coordinates of the station ($x_k, y_k, z_k$) and the hypocenter ($x_i^*, y_i^*, z_i^*$). Since the relations between the arrival times and earthquake locations are nonlinear, truncated Taylor series are used in the general case to linearize equation (1). In this case, the difference between the arrival times for the $i$th event is linear with respect to the corrections $\Delta m^i$ (four current corrections to the hypocenter parameters $\Delta x^i, \Delta y^i, \Delta z^i, \Delta \tau^i$ for each observation $k$). Assuming that the corrections are sufficiently small, the function of the arrival time can be extended from equation (1) to Taylor series with respect to the powers of the corrections leaving only the first terms of the extension to find the residual difference $r_k^i$

$$\frac{\partial T_k^i}{\partial m^i} \Delta m^i = r_k^i,$$ \hspace{1cm} (2)

where

$$r_k^i = (r_k^i)^{obs} - (t_k^i)^{cal},$$ \hspace{1cm} (3)

$$\Delta m^i = (\Delta x^i, \Delta y^i, \Delta z^i, \Delta \tau^i),$$ \hspace{1cm} (4)

where $(r_k^i)^{obs}$ and $(t_k^i)^{cal}$ are the observed and calculated arrival times from the $i$th event to the seismic station $k$, respectively.

The system of linear equations (2) with four unknown variables $\Delta m^i$ (three hypocentral parameters and time in the source) is solved using least squares iterations. First, a solution is specified in the form of double differences (5); containing corrections to the hypocenter parameters $\Delta x, \Delta y, \Delta z, \Delta \tau$ for each observation $k$. This solution is later checked for finding the corrections to the initially specified location. Next, the corrected solution becomes the input solution and so on. This method was first suggested by Geiger [9]. The iteration process rapidly converges if the initial determination of the hypocenter is close to its true location. A one-dimensional velocity model of the Earth’s crust is generally used in the calculations. It can be supplemented with details as the instrumental data on the earthquake sources are accumulated.

The accuracy in determining the hypocenter coordinates depends on the geometry of the seismic network, the available phases, the measurement accuracy of the arrival times, and the velocity model of the Earth’s crust [10, 11]. Application of a one-dimensional velocity model to determining the coordinates constrains the accuracy, because three-dimensional variations in the seismic wave velocities can introduce a systematic bias in the calculated arrival times. The variations in the velocities can be partially taken into account by introducing corrections to the calculation algorithm or velocity model of the earth’s crust for each station [8, 13].

The errors in specifying the velocity model are efficiently minimized using the methods of relative determination of the earthquake sources [7, 12]. If the distance between the hypocenters of two earthquakes is small compared to that between the earthquake source and the station and to the wavelength of the velocity inhomogeneity, the ray paths between the source and receiver coincide over almost the entire extension. In this case, the arrival time difference for two observed events can be related to the spatial difference in the source locations. In this approximation, the residual (double) difference $d_{ij}^r$ between the measured and calculated arrival times of seismic waves from two earthquakes $i$th and $j$th with allowance for (3) can be written as

$$d_{ij}^r = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal}.$$ \hspace{1cm} (5)

Equation (5) allows us to use both the phases with measured arrival times, in which absolute arrival times are input parameters and cross-correlation relative differences of the arrival times of seismic waves.

In the general case, the equation for the residual difference between the $i$th and $j$th events is obtained from (2):

$$\frac{\partial T_k^i}{\partial m} \Delta m^i - \frac{\partial T_k^j}{\partial m} \Delta m^j = d_{ij}^r.$$ \hspace{1cm} (6)

This equation is combined for all the events and all the stations by joining (5) and (6) to obtain a system of linear equations in the following form:

$$WGm = Wd.$$ \hspace{1cm} (7)

where $G$ is a matrix with size $N \times 4N$ ($m$ is the number of double differences, $N$ is number of events), which contains partial derivatives; $d$ is a vector containing double differences (5); $m$ is the vector $[\Delta x, \Delta y, \Delta z, \Delta \tau]^T$ of length $4N$ containing corrections to the hypocenter coordinates to be determined; and $W$ is a diagonal matrix with weight corrections for each equation. The weights are used to account for the accuracy in determining the arrival times of seismic waves and the influence of the source mechanisms in manual processing of seismograms. The coherence function for the waveforms considered here is used for cross-correlation data. The equation system of type (7) is solved using the decomposition or conjugate gradient (for a large body of data) methods.

The double difference method [14] is an effective tool for joint relocation of hypocenters of closely spaced sources and simultaneous relocation of a great number of earthquake hypocenters spaced at relatively
large distances from the observation stations. Joining the arrival time differences for P- and S-waves obtained from cross-correlation analysis with those obtained from the catalogue and minimizing the residual differences (or double differences) for earthquake pairs, it is possible to minimize the vector difference between their hypocenter locations. Thus, the distance between events can be specified without station corrections.

INITIAL DATA

Since the middle of 2001, an increase in seismic activity was recorded by the local digital seismic network in the southern part of Sakhalin. From July 22 to September 30, a peak of activity was recorded in the form of an earthquake swarm including approximately 300 foreshocks and 800 aftershocks in the magnitude range $M_L$ from 1.5 to 4.8 with a source depth $h$ equal to 15 km. The main shock with $M_L$ 5.2 and $M_L$ 5.6 was recorded between two en echelon segments of the active Aprelovskii fault on September 1, 2001.

The bulletin of the P- and S-wave arrival times based on the earthquake record by the local seismic network was used to relocate the coordinates of the hypocenters. The hypocenter parameters were initially determined by Kim Chun Un using the inversion method at the Laboratory of Seismology at the Institute of Marine Geology and Geophysics, Far Eastern Division of the Russian Academy of Sciences with the production of a catalogue of the recorded events [2]. The data obtained simultaneously by at least four stations (by one independent coordinate and time in the source for each degree of freedom) were used to relocate the coordinates. The arrival times with discrepancies yielding an error of the coordinate determination more than 5 km were excluded from the data processing. A total of 730 events from 1100 events recorded by the seismic network were selected. On the average, each earthquake was characterized by 9 independent determinations: 5 stations for the arrival times of P-waves and 4 stations for S-waves. In 2001, 10 temporal stations were set up in the southern part of Sakhalin; there were only four of them after the main shock. Some of them were located near the source region (Fig. 1), which allowed us to obtain reliable estimates of the earthquake source depth. A one-dimensional velocity model of the Earth’s crust based on the deep seismic sounding (DSS) data was used in the calculations [5]. A graph of the velocity distribution of the P-waves with depth is shown in Fig. 2. The velocities of the S-waves were calculated on the basis of the P-wave velocities using the relation $V_P/V_S = 1.73$.

The location of the seismic stations was determined with high accuracy ($\pm 15$ m) using GPS.

RELOCATION RESULTS

The coordinates of 730 selected hypocenters of the Takoe swarm were relocated using the double difference method [14]. For a more reliable estimate of the coordinates, the position of event clusters was relocated relative to reference points. The selected reference points corresponded to a strong foreshock on August 8, 2001, ($M_L$ 4.5, $h = 12$ km) and main shock on September 1, 2001 ($M_L$ 5.6, $h = 10$ km). Using the multichannel capstral technique [4], the depths of the sources of the reference shocks were relocated with an accuracy equal to $\pm 1$ km. The relocation of the hypocenters using the double difference method showed a notable decrease in their scattering (Fig. 3): the root-mean-square errors (averaged over all the events) decreased by a factor of approximately 2–2.5 times so that the average accuracy of the coordinate estimates after the relocation was equal to $\pm 1$ km.

The relocated hypocenters of the shocks are clearly grouped in space and time with a notable spatial separation between the foreshock and aftershock sources.

The following conclusions can be made on the basis of a detailed analysis of the spatiotemporal distribution of the earthquake sources and an analysis of the seismic activity.

The Takoe earthquake on September 1, 2001, ($M_W$ 5.20) in south Sakhalin was preceded by several phases of seismic activation, whose beginning was recorded 40 days before the main shock (Fig. 4). Within 20–40 days before the main shock, the preliminary activity was observed at the relatively low-seismic eastern wall of the active Aprelovskii fault at depths of 10–15 km (Fig. 5). The main shock ($M_L$ 4.5) in this phase occurred on August 8, 2001, at a depth of 12 $\pm$ 1 km.

It is seen from the comparison of Figs. 5 and 7 (upper left figures) that the northeastern trend of the epicenter cloud in Fig. 5 correlates well with the present-day NW–SW compression direction in south...
Sakhalin, as distinguished from the GPS observations [6]. The analysis of the group source mechanisms of the aftershocks of the Takoe earthquake also points to the fact that the major part of the strong foreshocks ($M_L > 3$) appeared under the conditions of obliquely (NE–SW) oriented compression with the predominance of reverse faults and normal faults as a seismic source mechanism [2]. It is noteworthy that the form of the initial pulse in the source differs for the foreshocks and aftershocks. The foreshocks of the first phase of the swarm development were characterized by a double pulse in the initial record of a $P$-wave (Fig. 9) up to the appearance of the strongest foreshock ($M_L 4.5, h = 12$ km) on August 8, 2001, presumably pointing to similar and unusual source mechanisms at this phase of the seismic activity.

As can be seen from these data and Fig. 5, the primary zone of local instability appeared in the lower part of the seismogenic crustal layer at depths of 10–15 km. Then, the region of local destruction gradually displaced in the direction of the regional compression to the active fault and in the upper part of the seismogenic layer to depths of 5–10 km. It follows that the seismic activation in the source region could be a response to an episode of viscous deformation in the lowest more viscous part of the seismogenic layer (or under it), which was caused by regional lithospheric compression with further transfer of excitation to the zone of the active fault and upwards in a more elastic part of the seismogenic layer.

A strong foreshock ($M_L 4.5$) occurred on August 8, 2001, in the end of the first activation phase at a depth of 12 ± 1 km, immediately in the active fault zone (Fig. 5), and it led to a sharp change in the spatial distribution pattern of the shocks observed during the next phase of the swarm development within 19–4 days before the main shock (Fig. 6). During this period, the local destruction almost uniformly spanned a significantly greater volume over all the depths of the seismogenic

![Fig. 3. Distribution of earthquake sources. (a) before relocation; (b) after relocation; (1) Reference points, (2) earthquakes. The upper figure shows the distribution of earthquake sources by epicenters; the middle and lower panels show depth sections in the directions $A–A′$ and $B–B′$, respectively.](image-url)
layer from 5 to 15 km. The general number of shocks decreases with time, as takes place in a common aftershock sequence (Fig. 4). It should be noted that during this period, a notable number of shocks appear at the western wall of the active fault generally at depths of 5–10 km, i.e., near the hypocenter of the future main shock, which was not observed at the first phase.

Further events showed that the occurrence of a strong shock ($M_L 4.5$) on August 8, 2001, led only to partial stress relief of the entire source region, which was, however, insufficient for relaxation of the transferred initial excitation. Given the appearance of shocks in the western active fault wall at depths 5–10 km at this stage, the excess stresses transferred with the initial excitation started to affect the entire western fault wall during the second phase of the swarm development. The GPS data [6] point to the intense accumulation of deformations in the active Aprelovskii fault zone and most likely in its western wall at depths of 5–10 km. Thus, the forcing of excess stresses generated a zone of local concentration of destructions precisely in this region (Fig. 7).

It is seen from Fig. 7 that a narrow zone of local concentration of destructions at depths of 5–10 km was formed within 1–3 days before the main shock with $M_L 5.6$ at the western wall of the active fault. The third phase of the swarm development was marked by the strongest foreshock ($M_L 4.8$) in the lower part of the forming zone at a depth of approximately 10 km, i.e., practically at the same point, at which the main shock later occurred. The slope of the recurrence graph for the shocks of the third phase is anomalously low [3], which corresponds to the deficiency of the weak earthquakes. According to the opinion of some investigators, this was caused by redistribution of stresses in the fault.
Fig. 6. Spatial distribution of the Takoe earthquake swarm sources during the second phase (19–4 days before the main shock).

Fig. 7. Spatial distribution of the Takoe earthquake swarm sources during the third phase of the foreshock development (1–3 days before the main shock with $M_L 5.6$, which occurred on September 1, 2001).

The mechanism of the main shock based on the deep seismic sounding (USA) is shown in the upper left panel; the black quadrants correspond to the regions of the arrival of compression waves; $P$ is the orientation of the axis of maximal compression.
The main shock with $M_L 5.6$ occurred on September 1, 2001, at a depth of 10 km in the lower border of the formed narrow zone of destruction concentration (Fig. 7). The source mechanism shown in the figure demonstrates that a pure reverse fault occurred in the source along a plane that was normal to regional compression and dipped in the northeastern direction. Based on the GPS data, the displacement in the source was oblique to the strike of the active fault and parallel to the direction of the regional compression [6]. The meridional orientation of the active fault in this case plays a subordinate role in the formation of the destruction plane in the main shock source. The determining factor is the direction of the regional compression affecting the entire lithospheric column.

The fourth phase of the evolution of the Takoe earthquake swarm is the aftershock stage. After the main shock, an enormous number of aftershocks occurred in the reverse wall mainly at depths of 5–7 km (Fig. 8). The strongest aftershock ($M_L 4.5$) occurred at a depth
of approximately 6 km. The redistribution of stresses after the main shock was mainly related to the structural geological factors rather than to the orientation of the regional stress. It is seen from Fig. 8 that the aftershock cloud is generally extended along the strike of the active fault with the bulk of the aftershocks occurring in the depth range of 5–7 km, where the accumulation of elastic deformations caused by the general regional compression of the fault zone is likely to occur.

CONCLUSIONS

The relocation of the hypocenter of the 2001 Takoe earthquake swarm makes it possible to clearly trace all the phases of the earthquake swarm development between two enechelon segments of the active Aprelovskii fault: (1) the initiation phase of the primary zone of local instability in the eastern flank of the fault at depths of 10–15 km; (2) gradual westward migration of the sources to the active flank of the fault; (3) partial stress relief of the entire source region after the strong shock with ML 5.6; and (4) formation of a narrow zone of concentration of destructions at depths of 5–10 km in the western fault wall immediately before the main shock with ML 5.6; and (5) the phase of numerous aftershocks, most of which appeared in the western wall of the fault at depths of 5–6 km. It was established that the foreshock and aftershock phases significantly differ in some source parameters. The general pattern of the evolution of the Takoe earthquake swarm and the deduced source mechanisms [2] agree well with the northeastern–southwestern direction of the present-day regional compression in south Sakhalin distinguished from the data of GPS observations [6] and with the configuration of the active fault zones in this region based on the data of paleoseismological investigations [1].

Paleoseismological studies by M.I. Streltsov and A.I. Kozhurin demonstrated that the last catastrophic earthquake (M ≥ 7.5) in the region of the Aprelovskii fault occurred 800 years ago [2]. Detailed studies of the seismic processes that occurred in the fault zone, for instance, the 2001 Takoe earthquake swarm, can be useful for searching for criteria for the preparation of a strongly destructive earthquake in the fault zone.

The obtained results also highlight the need for more detailed research of the lower crustal processes and the interaction between faults in the complex fault system of the region.

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REFERENCES


