ISSN 0016-8521, Geotectonics, 2017, Vol. 51, No. 6, pp. 584–590. © Pleiades Publishing, Inc., 2017.
Original Russian Text © A.L. Strom, V.S. Imaev, O.P. Smekalin, A.V. Chipizubov, A.N. Ovsyuchenko, N.N. Grib, A.A. Syas'ko, 2017, published in Geotektonika, 2017, No. 6, pp. 58–65.

Seismotectonic Investigations of the Chulmakan Fault, Southern Yakutia, to Assess the Seismic Hazard for the East Siberia–Pacific Ocean Oil and Power of Siberia Gas Pipelines

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Received February 28, 2017

Abstract—Based on analysis of space images and maps, the data of laser scanning, trenching, and field geophysical and seismotectonic studies in southern Yakutia, the Chulmakan seismogenic fault is mapped and characterized. The structure and parameters of seismogenic deformations of this fault, which crosses the Power of Siberia gas pipeline, are determined. A preliminary estimate of the Chulmakan seismodislocation age is given, as well as the magnitude of the corresponding paleoearthquake. The level of potential seismic hazard at the site where the Chulmakan Fault crosses the East Siberia—Pacific Ocean oil pipeline and Power of Siberia gas pipeline is determined.

Keywords: seismodislocation, paleoearthquake, active fault, seismic hazard, trenching, East Siberia—Pacific Ocean oil pipeline, Power of Siberia gas pipeline

DOI: 10.1134/S0016852117060073

INTRODUCTION

The aim of the present work is to study the Chulmakan paleoseismodislocation (PSD), which was recently revealed in the northeastern margin of the Chulman Basin within the limits of the Aldan Shield, Siberian Platform. Seismogeological studies of active faults make it possible to estimate the seismic potential, recurrence of earthquakes with maximum magnitudes, and other parameters to predict possible seismic impact on designed engineering structures in the future. These studies are especially important for the sparsely populated regions of Siberia and Russian Far East, whose seismological statistics cover time intervals of no more than 100–300 years.

Seismogenic dislocations in the zone of the Chulmakan Fault were revealed by the authors for the first time in 2005, during studies to assess the seismic hazard along the course of the East Siberia—Pacific Ocean oil pipeline [1–4, 7]. This fault cuts the eastern Chulman Basin in the latitudinal direction; the basin is of Mesozoic age and filled by predominantly Jurassic conglomerates and carboniferous sandstones occurring immediately on the Precambrian granitoid basement in the inner part of the Aldan Shield [9]. The renewed segment of the fault, which is expressed in relief as an escarpment, is at least 25 km long. At particular sites, the escarpment has clear seismogenic signatures. Seismic slips on the Chulmakan Fault led to vertical displacement of the formerly united subhorizontal flattened surface to the new elevation levels. The difference in elevation difference along the escarpment varies from one to several meters.

Seismogeological investigation of the dislocations along the Chulmakan Fault was carried out in the site where it crossed the East Siberia—Pacific Ocean oil and Power of Siberia gas pipelines, northeast of the city of Neryungri, and included the following works:

comprehensive morphometric analysis on the basis of remote sensing data (laser scanning and space images) and ground-based measurements;

trenching, i.e., excavations of deformations by digging trenches of various sizes in several sites;

geophysical methods for small-depth studies.

MORPHOLOGICAL PECULIARITIES OF THE CHULMAKAN DISLOCATION

Based on interpretation of space images, the escarpment of the Chulmakan Fault is traced in relief

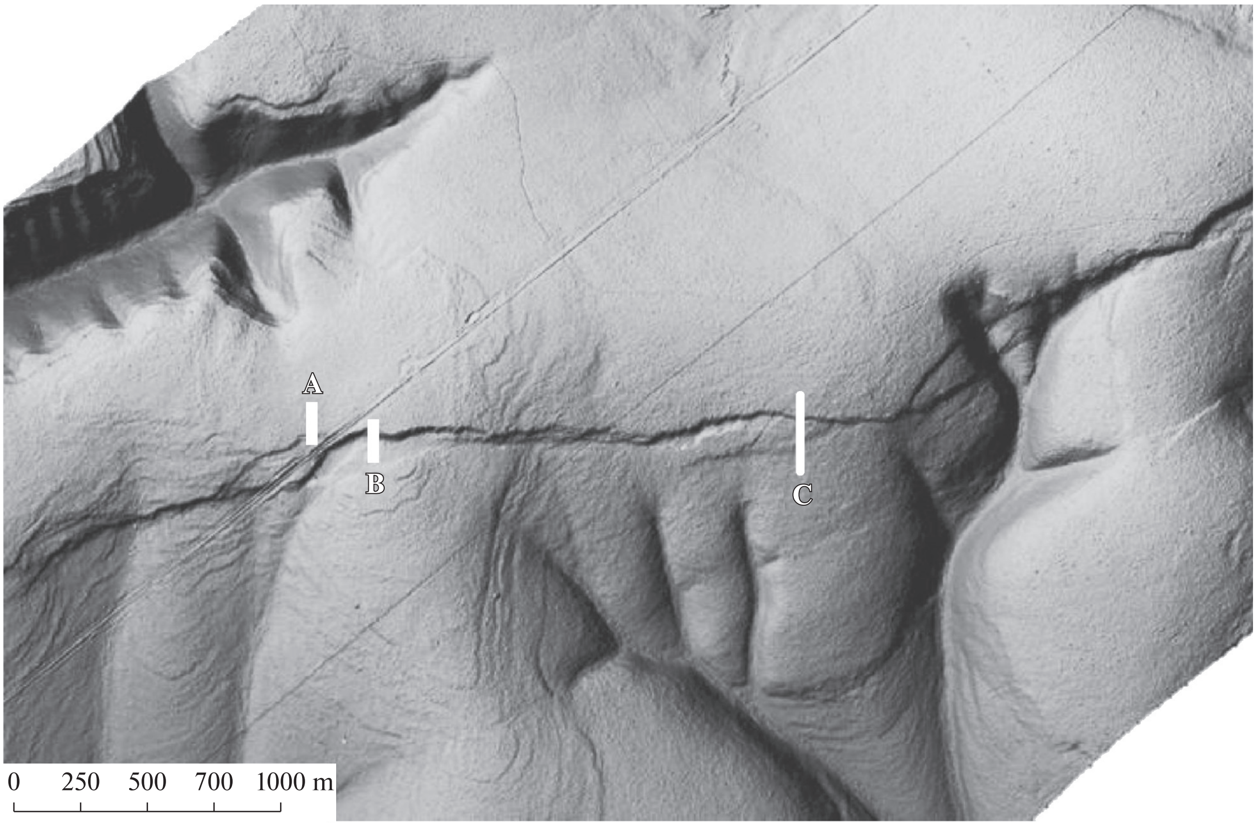

Fig. 1. Digital elevation model for Chulmakan fault with well-expressed escarpment in fault zone. Profiles A and B correspond to trenches dug out in 2007; C, trenching and geophysical works in 2016.

on a weakly sloped hilly ancient planation surface, which forms plateaulike watersheds between the main rivers; all features of the Chulmakan Fault expression in the contemporary relief indicate it is an active fault [5, 6, 12, 15]. In plan view, the escarpment is a curved line consisting of northeast- and sublatitudinally trending segments. Somewhere the fault is represented by en echelon series of scarps and detachment cracks indicating a sinistral shear component of the slip. However, we have not found any direct signs of horizontal displacement in the form of regular shift of landforms crossing the escarpment. This is probably explained by the fact that the available highly detailed digital elevation models contain the fragment of the fault at the site where it runs on the planation surface weakly cut by rivers.

The height of the escarpment varies from a few to 13–15 m. Where the escarpment changes its trend from northeastern to sublatitudinal, the characteristic features are grabens at the base of the escarpment; this indicates tension along about 157°–337° ± 8° and, indirectly, a sinistral shear component of slip in sublatitudinal segments. The depth of grabens without their sedimentary filling is up to 2.0–2.5 m with a width up to 140 m.

TRENCHING

In order to study the structural peculiarities and determine the genetic type of deformation, we performed trenching in the Chulmakan Fault zone. In 2007 trenching works were carried out at a site located close to where the fault crosses the East Siberia–Pacific Ocean oil pipeline (Fig. 1, profiles A and B), and in 2016 we trenched the site where the fault was to cross the Power of Siberia gas pipeline (Fig. 1, profile C).

Trenching was done to study the structure of seismogenic deformations. Trenches were dug out across the escarpments to expose the dislocations in Jurassic sandstones and superimposing eluvium and deluvium. Thickness of Cenozoic (predominantly Pleistocene–Holocene) deposits is no more than 2–3 m, which is quite normal for the watershed parts of planation surfaces. In this respect, we trenched the seismogenic ruptures that deformed both loose young deposits and bedrocks.

The main signatures indicating the seismogenic character of the studied deformations are colluvial wedges at the base of the escarpment, which join the fault plane and are represented by rock debris from the exposed surface of the escarpment. In many places along the escarpment, erosion of the exposed surface is not finished: it is not sodded and not even com-

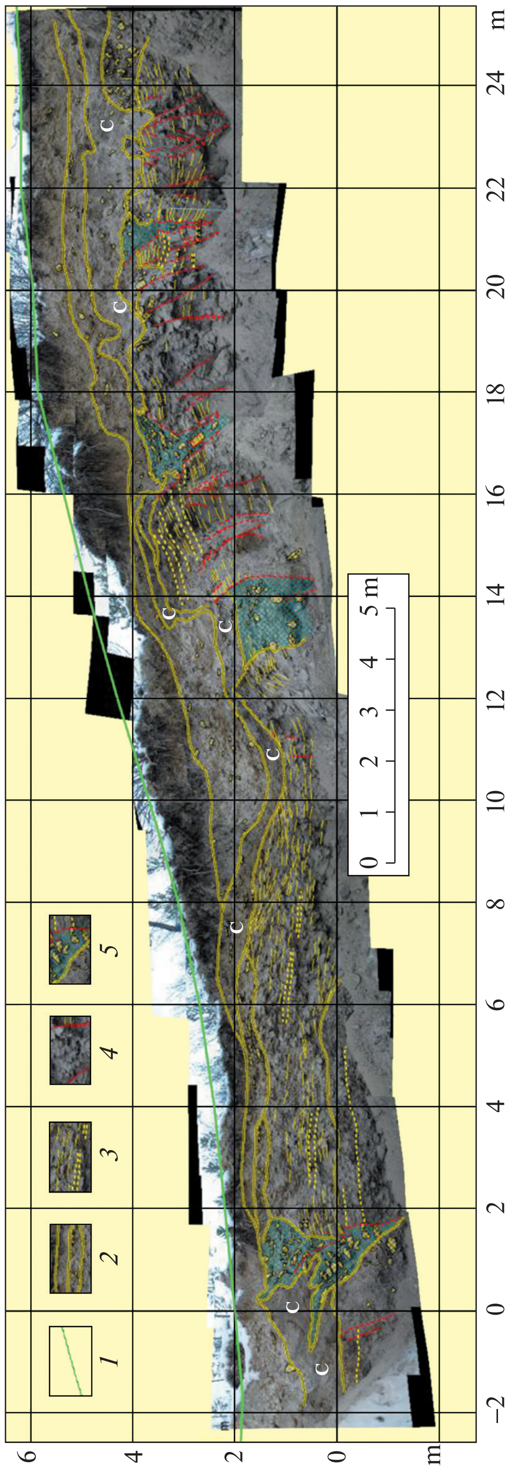

Fig. 2. Interpreted cross section of seismogenic deformations from images made for western wall of trench, with denoted boundaries. (*1*) Surface profile based on manual leveling; (*2*) boundaries of layers having different lithologic compositions in loose bedrocks; (*3*) bedding direction in Jurassic sandstones, sandy loam interbeds, and sandy lenses; (*4*) ruptures; (*5*) gaping cracks filled with loose deposits.

pletely covered by loose deposits; this can be an indirect sign of the relatively young age of the studied dislocation.

In the trenches dug out in 2007, the main fault plane was steeply inclined toward the footwall. In the trench dug in 2016, the main fault plane was almost vertical when it reached the trench bottom, indicating a normal faulting kinematics of the dislocation. The conditions of extension perpendicular to the fault were also indicated by gaping cracks oriented in parallel to the course of the main rupture; they were located predominantly in the hanging wall and had the signatures of normal-fault microslips, although gaping cracks can also form in a hanging wall in the case of reverse-fault slip along a fault [15, 16]. Such coseismic features as injection dikes and convolutions in loose deposits were also reported in the trenches at the bases of escarpments framing the subsided near-fault block. The vertical amplitude of singular slips was 1.0–1.5 m. In the trenches we collected samples for radiocarbon dating. The obtained absolute age indicates that the fault was activated 1500 ± 270 and 3900 ± 350 years B.P. based on radiocarbon analysis (or 1580 ± 220 and 3890 ± 320 years B.P. based on calendar or calibrated age) [2–4].

The recent trenching in 2016 was carried out in the site where the Chulmakan Fault crosses the Power of Siberia gas pipeline. The seismogenic escarpment here was about 4 m high, which with the surface inclination taken into account corresponds to the total vertical displacement of the initial surface by 2.5–2.6 m. The trench of 27 m long and up to 4.5 m deep was dug out across the escarpment. The excavated depth exceeded the amplitude of the fault offset. It suggested the necessity of revealing the reference layers in the fault walls already at the stage of planning the trench in order to determine exactly the singular slip amplitudes. The width of the dug-out trench (at least 3 m at the day surface level) allowed us to perform photo documentation of the cross sections in both walls and to quickly compile a diagram of deformation structure (Fig. 2).

In terms of stratigraphy, the cross section of the trench is represented by Jurassic and Quaternary deposits. The visible thickness of Jurassic sandstones is at least 3 m. Sandstones are weathered, have cracks within layers, laminated along their bedding planes, and contain interbeds and lenses of siltstones. The layers occur horizontally, with a slight local deformation observed only near the escarpment (the slope is up to 10–15°). Sandstones on either side of the main fault plane are characterized by different degrees of postsedimentation alterations, colors, and amounts of nonsandstone material; thus we can refer the rocks in the hanging wall to earlier units compared to those in the footwall. Hence, the total amplitude of slip on the fault exceeds the visible thickness of sandstones, and the activation time was earlier than the Quaternary. Upsection, sandstones gradually change to eluvium and then become covered by loose Quaternary deposits up to 2.0–2.5 m thick.

The main fault plane, the slips on which formed the escarpment, is a gently curved plane along the dip direction and in plan view. The specific change of the fault plane direction from vertical at the trench bottom to tilted toward the footwall is caused by (a) gradual stepwise shifts of small sandstone units under the effect of gravity and (b) displacement of the near-surface layer downslope. The deformation of the exposed surface of the fault plane was also caused by the formation of a tension-induced crack at the base of the normal-fault escarpment; after the earthquake occurrence, this crack was filled by loose deposits. Examples of similar curved fault planes, changing up to a reverse dip, are presented in [12, 19, 21].

The hanging wall has superimposed micrograbens and wedgelike extension cracks filled with detrital material. Remarkably, extension cracks in the northern part of the trench are filled with dense gray sandy loam, whereas the wide extension wedge structure cuts this layer. The same sandy loam layer is clearly deformed above the main fault plane. Such a combination of deformations, which are expressed in both slips on the main fault and the formation of cracks in the hanging wall, indicates there were two seismic events that formed seismogenic ruptures.

GEOPHYSICAL STUDIES

Comprehensive application of small-depth geophysical methods allows the internal structure of dislocation to be investigated down to several tens of meters deep. Geophysical works in 2016 were conducted in parallel to trenching. A geophysical profile 480 m long was made along the axial line of the clearcut prepared for later construction of the Power of Siberia gas pipeline. The employed geophysical methods included radar probing, refraction correlation method (RCM), electrical survey by axial dipole sounding (ADS), and magnetometry (Fig. 3).

On the curve of the anomalous magnetic field, the site with the seismogenic escarpment is characterized by maximum negative values (–20 nT) for background values falling within the interval from –10 to +10 nT. Remarkably, negative values of magnetic anomalies are characteristic of the footwall of the fault, whereas positive values are observed in the hanging wall. This indicates different composition of rocks divided by the faults, as already noted above. The negative maximum corresponding to exposure of the fault plane on the surface is probably related to filling of a burrow at the base of the escarpment with rocks from the hanging wall.

In the geoelectrical cross section, the main fault zone is expressed as a steeply dipping narrow band of low specific resistance. This band is clearly noticeable in the high-resistance background and its position clearly fits the seismogenic escarpment. With depth, the low resistivity zone shows a higher deviation toward the footwall, but this does not contradict the normal-fault character of the dislocation. The linear low-resistivity anomalies identified in the uplifted footwall of the fault have a smaller extent of depth and can therefore be attributed to opening cracks.

In the RCM velocity cross section, the inhomogeneous anomalies tend to the ruptures. In the radar probing cross section constructed on the basis of central frequency isolines immediately beneath the escarpment, it is possible to identify a zone dipping toward the sunken wall, characterized by a permeable medium frequency of about 60 MHz. However, at other sites, the cross section is generally characterized by significant inhomogeneities, which are likely related to fracturing of the medium.

DISCUSSION

The Chulmakan Fault extends toward the sites of major planned construction in southern Yakutia (the Kankun hydroelectric on the Timpton River and the El'kon mining and concentrating mill), crosses two largest pipeline systems in Russia (the East Siberia–Pacific Ocean oil pipeline and Power of Siberia gas pipeline), and is affected by the Olyokma-Stanovoy seismoactive zone [2, 4, 7, 9, 12, 17]. The seismic potential of the Chulmakan Fault determines the maximum possible shaking intensity for these objects and their infrastructure. Based on the known relations linking earthquake magnitudes with extent and kinematic characteristics of a source [8, 13, 15, 19, 21], Chulmakan Fault earthquakes can be more than 7.0 in magnitude and their shaking intensity at the sites of the mentioned objects can exceed the specified I = VIII on the MSK-64 by one to two points (Fig. 4). Since the construction of these objects is only about to begin, the shaking intensity level and possible residual deformations along the fault line must be taken into consideration and appropriate engineering solutions should be applied in order to provide higher earthquake resistance.

CONCLUSIONS

(1) The seismotectonic investigations carried out along the courses of the East Siberia–Pacific Ocean oil and Power of Siberia gas pipelines have specified the seismic hazard level for these linear facilities and revealed new, formerly unknown PSDs, of which one of the most significant is the Chulmakan PSD, whose structure has been analyzed in the present work.

(2) The revealed PSD size, primarily, the total length of singularly activated segments of the Chulmakan Fault (25 km) and the estimated vertical offset on the fault plane (1.0–1.5 m per each seismogenic slip) during two paleoearthquakes (calendar ages of 1580 and 3890 B.P.), has given us grounds to characterize the seismic hazard of the Chulmakan Fault zone

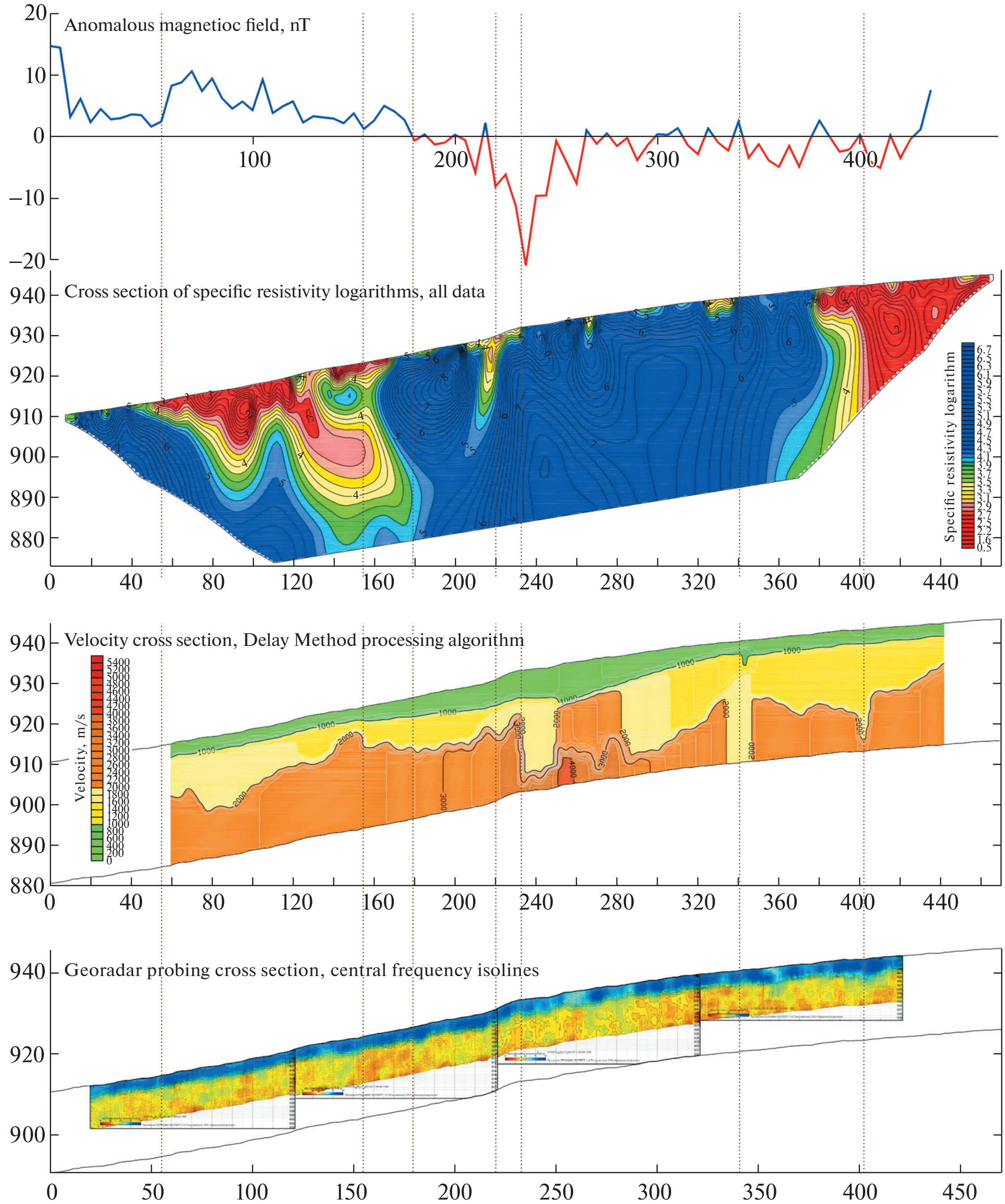

Fig. 3. Electrical survey profile across Chulmakan Fault based on different data (from top to bottom): magnetometry, ADS electrical survey, RCM seismic survey, radar probing.

with a potential magnitude of $M = 7.0$ and to estimate a possible shaking intensity it high as $I =$ VIII on the MSK-64.

(3) Recent paleoseismological and seismotectonic investigations by Russian specialists in different regions of Siberia, the Caucasus, Altai, Sayan, Tuva, and Mongolia show that this research is not only necessary, but mandatory when solving practical problems in the design and construction of any major engineering structures located in regions prone to seismic hazard.

(4) The seismotectonic and geophysical investigations carried out at the largest Russian pipeline systems (Power of Siberia gas and East Siberia–Pacific Ocean oil pipelines) and the unique trenches dug out across the revealed Chulmakan PSD are of both theoretical and practical value; note that the trenches and

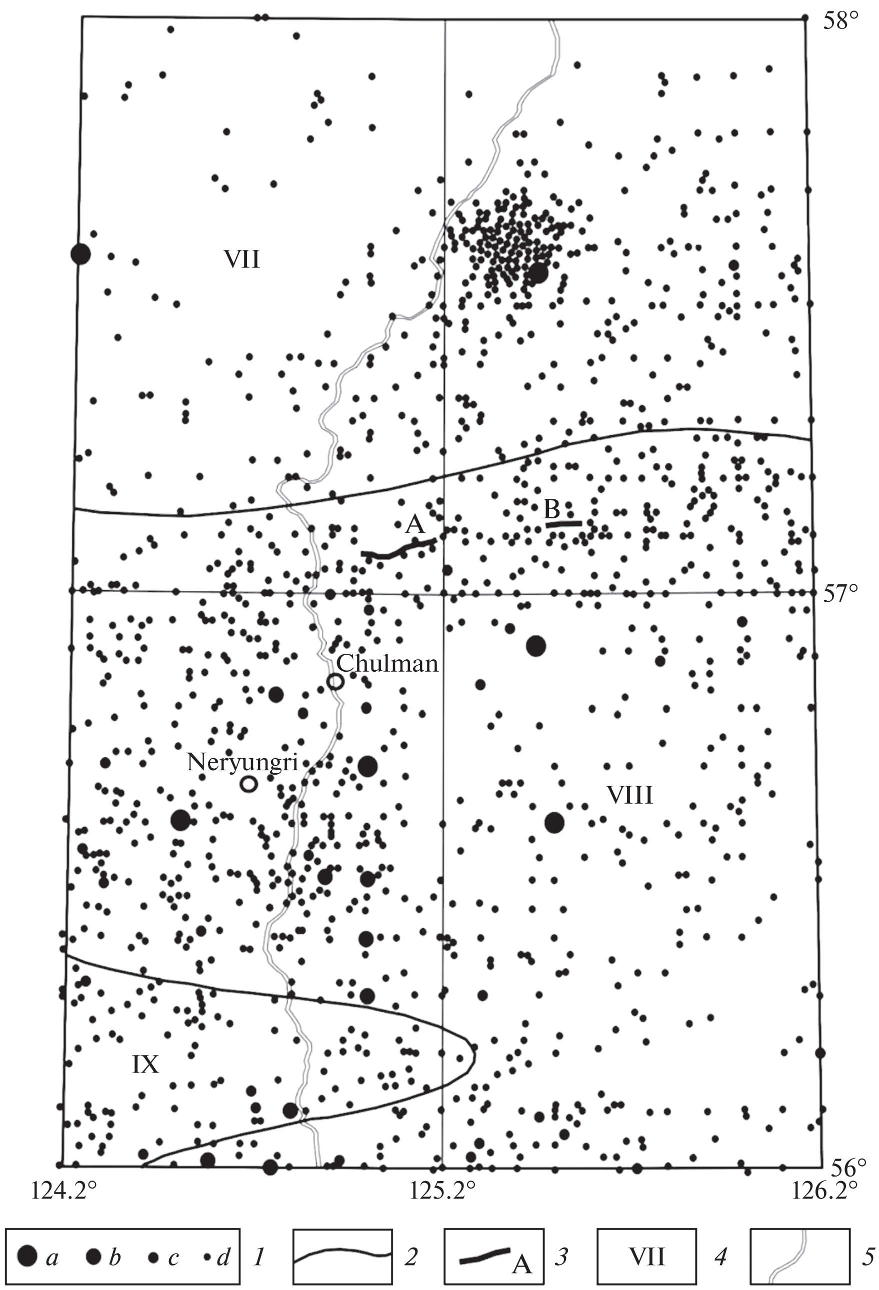

Fig. 4. Seismodislocations of faults in central Aldan Shield based on interpretation of satellite images and laser scanning results, with use of data from [1, 3, 4, 7, 9, 14]. (*1*) Epicenters of earthquakes, based on instrumental data for past 50 years, with different epicentral energies (energy class, K): (a) K = 11–12, (b) K = 10, (c) K = 9, (d) K ≤ 8; (*2*) boundaries of zones characterized by different potential seismic hazard (shaking intensity on the MSK-64); (*3*) paleoseismodislocations (A, Chulmakan; B, others); (*4*) seismic hazard level (shaking intensity on the MSK-64); (*5*) Amur–Yakutsk highway.

their sites can be further used as engineering–geological and geophysical test areas.

ACKNOWLEDGMENTS

The work was supported by the Russian Foundation for Basic Research (project no. 16-05-00224), the Russian Science Foundation (project no. 15-17-20000), and by a grant from the Government of the Sakha Republic (Yakutia) for a comprehensive study of the territory of the Republic in 2016–2020. The authors thank the reviewers for useful notes and OOO Neryungrigeofizika for the materials used when constructing the electrical survey profile.

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Reviewers: Yu.A. Volozh, V.G. Trifonov

Translated by N. Astafiev

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