Environmental effects of the 2011–2012 Tuva earthquakes (Russia): Application of ESI 2007 macroseismic scale in the Siberian mountains

A. N. Ovsyuchenko[1,2], E. A. Rogozhin[1], A. V. Marakhanov[1], Yu. V. Butanaev[2], A. S. Larkov[1], and S. S. Novikov[1]

Received 1 December 2016; accepted 22 December 2016; published 18 December 2016.

The data on the environmental manifestation of the Tuva earthquakes 27.12.2011 ($Ms = 6.7$) and 26.02.2012 ($Ms = 6.8$) are presented. The earthquake effects are distinctly divided into two groups: the secondary effects as result of the seismic shaking and primary effects which are directly related to the seismic rupture at the surface. The small length of the seismic ruptures of both earthquakes comparing to the magnitude is their distinctive feature. The data on the distribution of the total secondary effects of both earthquakes are collected. The shock intensity map (ESI 2007 scale) is compiled. For the case of the Tuva earthquakes ESI 2007 scale proves to be of an indispensable tool because of the other criteria lack for the assessment of the shock effects within the epicentral area. The use of the ESI 2007 scale revealed some difficulties in its application for the Siberian mountain: the scale did not consider the difference between permafrost and not permafrost soils, as well as between winter and summer conditions. Obviously the earthquake manifestations widely vary depending on these conditions in Siberian continental climate. Nevertheless the use of scale allowed us to obtain a large amount of new data on the effects of strong seismic events in the Altai–Sayan region. *KEYWORDS:* Earthquakes; earthquake source; seismic rupture; fault zone; secondary effects of earthquake.

Citation: Ovsyuchenko, A. N., E. A. Rogozhin, A. V. Marakhanov, Yu. V. Butanaev, A. S. Larkov, and S. S. Novikov (2017), Environmental effects of the 2011–2012 Tuva earthquakes (Russia): Application of ESI 2007 macroseismic scale in the Siberian mountains, *Russ. J. Earth. Sci., 17,* ES1002, doi:10.2205/2017ES000590.

1. Introduction

In 2011–2012 two earthquakes with $Ms = 6.7$ and 6.8 have occurred in the South of Siberia (Tuva Republic, Russia), within the Altai–Sayan mountain. These seismic events turned out to be the strongest for the all history of the seismological observation in Tuva and became the first well studied earthquakes of this region. They did not accompanied by human lost however had the serious consequences evoking big tumult among the local population and attracting the close attention of the geologists and seismologists.

The earthquake occurred in a remote mountain-taiga area without permanent population. That is why ESI (Environmental Seismic Intensity) 2007 scale was the main tool for the assessment of the earthquake consequences [*Michetti et al.*, 2007]. The scale is based on the earthquake environmental effects – any natural earthquake consequences. Recognition of the role of the ESI 2007 scale for the assessment of the earthquake intensity relating as to the modern as well as to paleoearthquakes is increasing among the specialists. For the case of the Tuva earthquakes ESI 2007 scale proves to be the indispensable tool because of the practical lack of other criteria for the assessment of the shaking effects within the epicentral area.

[1]Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences, Moscow, Russia
[2]Tuva Institute for Exploration of Natural Resources, Siberian Branch of the Russian Academy of Sciences, Kyzyl, Russia

http://elpub.wdcb.ru/journals/rjes/doi/2017ES000590-res.html

2. Instrumental Data and Seismotectonics of the Epicentral Area of the Earthquakes 2011–2012

The first Tuva earthquake occurred on December 27, 2011, about 100 km eastward of Kyzyl, the capital of the Tuva Republic. According to Geophysical Survey RAS data (GS RAS, http://www.ceme.gsras.ru) this seismic event had $Ms = 6.7$ ($Mw = 6.6$ – NEIC) and calculated intensity in the epicenter – VIII on the MSK-64 scale. After short aftershock process, two months later, February 26, 2012,

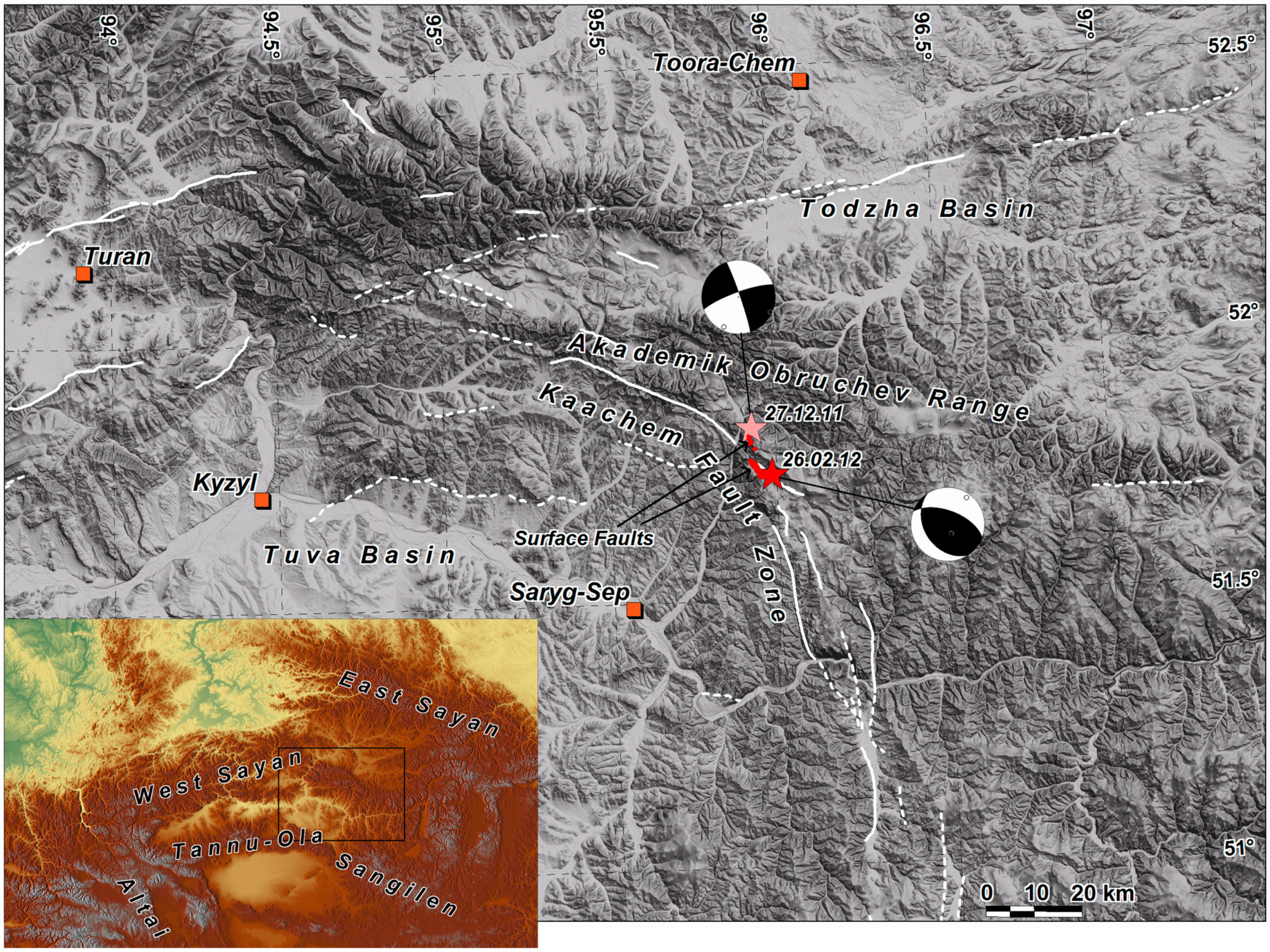

Figure 1. The position of the seismic rupture of the earthquakes 2011–2012 in the Kaahem system of the active faults. The white dashed lines show the supposed active faults, the continuous lines show the studied faults according to [*Arzhannikov*, 2000; *Arzhannikov, Zelenkov*, 1995]. The stars show the epicenters of Tuva earthquakes according to [*Emanov et al.*, 2014]. The source mechanisms are based on GS RAS. Basis on digital terrain model SRTM.

practically in that area, the second earthquake took place with $Ms = 6.8$ ($Mw = 6.7$ – NEIC) and calculated intensity in the epicenter – IX on the MSK-64 scale (GS RAS, http://www.ceme.gsras.ru). The depth of hypocenter of the first earthquake was estimated as $h = 17$ km, the second one $h = 14$ km [*Emanov et al.*, 2014]. The intensities of both shocks in the town Saryg-Sep, the nearest populated area, situated in 40 km from epicenter, were VII–VIII and VII on the MSK-64 scale, respectively.

The earthquakes occurred in Altay–Sayan region of the high seismicity [*Zhalkovsky et al.*, 1995]. The stress distribution in the seismic sources of the Altay-Sayan mountain region and Mongolia shows the typical near horizontally compressive stress oriented in submeridional and north-east directions [*Goldin, Kuchai*, 2007]. These data are well consistent with kinematics of the displacements along the active faults, formed under conditions of strike-slip and compression with strike-slip deformation [*Baljinnyam et al.*, 1993]. The Tuva earthquakes were governed by same regularities. According to focal mechanisms (GS RAS, http://www.ceme.gsras.ru, [*Emanov et al.*, 2014]), the motion of the first earthquake had mainly strike-slip kinematics; the second earthquake was characterized by predominated reverse fault kinematics with strike-slip components (Figure 1). The dextral horizontal strike-slip is typical for north-western plane; the left-lateral slip are characterized by the north-eastern plane.

The earthquakes occurred in the axial part of the mountain ridge named Academician Obruchev. It elevated over the surrounding intermountain deprtssion – Tuva and Todja. Within considered area the axial part of the mountain range is “planted” on the Kaahem fault and consists of the narrow ridges with altitudes up to 2500–2890 m, which are divided by the intermountain depressions and deeply incised by river valleys. The Kaahem fault is the largest crushing zone of 15–20 km wide, where the strongly deformed and metamorphosed Paleozoic rocks are developed. The rocks are broken by numerous faults of various directions and kinematics of displacements. The Kaahem fault zone experienced a complicated geological history and played an important structural role throughout the all tectonic and magmatic activations since the end of Precambrian [*Kudryavtsev, Kuznetsov*, 1966].

The Academician Obruchev range proved to be seismically moderately active for the half of century of the seismological observation. In 1960–1980 there were repeated earthquakes with moderate magnitudes ($M = 4-5.5$), however the epicentral area of earthquakes 2011–2012 was practically aseismic more than 50 years [*Emanov et al.*, 2014]. However the possibility of the strong earthquakes within Academician Obruchev ridge was determined with use of the seismogeological approaches. Based on the identification of the young (Quaternary) tectonic motion in the western part of the ridge *Chernov* [1978] had outlined the seismic generating structure, named Kaahem seismogen, partly coinciding with the same fault. Later the paleoseismological investigation revealed the traces of paleoearthquakes with $M = 6.6-7.0$ [*Arzhannikov*, 2000; *Arzhannikov, Zelenkov*, 1995]. Thus the earthquakes 2011–2012 did not became unexpected events from the point of view of the long-term seismotectonic forecast being emerged in already known seismic generating structure.

3. ESI 2007 Scale and Environment of the Epicentral Zone

The epicentral area is situated in a remote mountain-taiga area without permanent population, that is why the major investigated effects of earthquakes were in natural environment. The scale INQUA EEE (EEE – Earthquake environmental effects) worked out as a main guidance for evaluating the intensity of shaking [*Michetti et al.*, 2004]. The scale INQUA EEE was elaborated in the framework of the International Union for Quaternary Research (INQUA) in 2004. In 2007 after some improving it was named ESI 2007 (Environmental seismic intensity) [*Michetti et al.*, 2007].

In ESI 2007 scale the epicentral intensity is determined by two independent criteria – the size of the primary seismic ruptures and total area of the secondary effect distribution. In addition to distributing area the scale also considers the size of the secondary effects (the volume of the landslides and rockfalls, as well as the length and width of cracks, etc.). The size of the primary seismic rupture is characterized by its total length and maximal displacement.

The ESI 2007 scale was tested on many earthquakes including some events within Central Asia, Southern Siberia and Far East [*Berzhinsky et al.*, 2010; *Ovsyuchenko et al.*, 2013; *Tatevossian*, 2007; *Tatevossian et al.*, 2009, 2010] The scale testing was directed to the comparison of the estimates derived by traditional macroseismic scales (MSK, MM, EMS). As a whole ESI 2007 scale is satisfactorily correlated with traditional scales however it allows the restoring the more detailed picture of shocks in the epicentral area [*Serva et al.*, 2016]. Though it is obvious the results of the ESI 2007 scale application depend directly on the diversity of the natural conditions.

The earthquakes 2011–2012 occurred in winter, within a mountain area with sharply continental climate and well-developed permafrost. The vast watershed areas in the epicentral zone have a very gentle shape. Up to the absolute elevations 1850–2000 m they are covered with thick taiga, higher it is replaced by mountain tundra and vast fields of stone placers. As a rule the watershed slopes are very steep – 10–30°. As with other Siberian mountains within the slopes of the Academician Obrutchev ridge the seasonal covering displacement are strongly dominated in warm season while in the winter there is a full stabilization [*Ivanovsky, Vyrkin*, 2006]. During the earthquakes of 2011–2012 the slopes were chained by permafrost what did not let rising the EEE. An additional obstacle for this was also the dense taiga forest on the mountain slopes, covered with a strong root system. One more distinctive peculiarity of the region is strong predominance of the solid igneous, volcanic and volcano-sedimentary rocks of Paleozoic age, as well as a small thickness and mostly coarse clastic composition of the cover. All the listen factors resulted in the markedly restricted distribution and extent of the EEE, thereby "reducing" the average intensity of the Tuva earthquakes on the ESI 2007 scale.

Among the specific geological and geomorphological conditions of the important influence on the distribution and significance of EEE it is worth to mention as follow: the stability and steepness of slopes, composition of the basement and unconsolidated sediments, groundwater level, the vegetation pattern, the presence of permafrost and the time of year that sets the level of soil freezing. The account on these conditions applying the ESI 2007 scale is possible regarding the transfer from the intensity of the "objects" to the intensity in the "point" [*Guerrieri et al.*, 2007; *Tatevossian et al.*, 2009]. As the points are considered the main pattern of relief, for example, the small river valleys and mountain ranges, where the total seismic effect is estimated. This use of different spatial levels of the effect generalization significantly increases the stability of assessments to external factors. While the seismotectonic mapping of the primary seismic ruptures the attention was paid to the linear faults of the earth's surface with common signs of the tectonic deformation, described in the work [*McCalpin*, 2009].

4. The Results of the Field Investigation

The both earthquakes caused as primary seismic ruptures, expressing the earthquake source on the surface as well as secondary effects resulted from seismic shocks (Figure 2).

4.1. The Primary Faulting

The earthquake sources on the surface were expressed as seismic ruptures cut the roots and trunks of the trees, stones, shrubbery and all the relief forms [*Rogozhin et al.*,

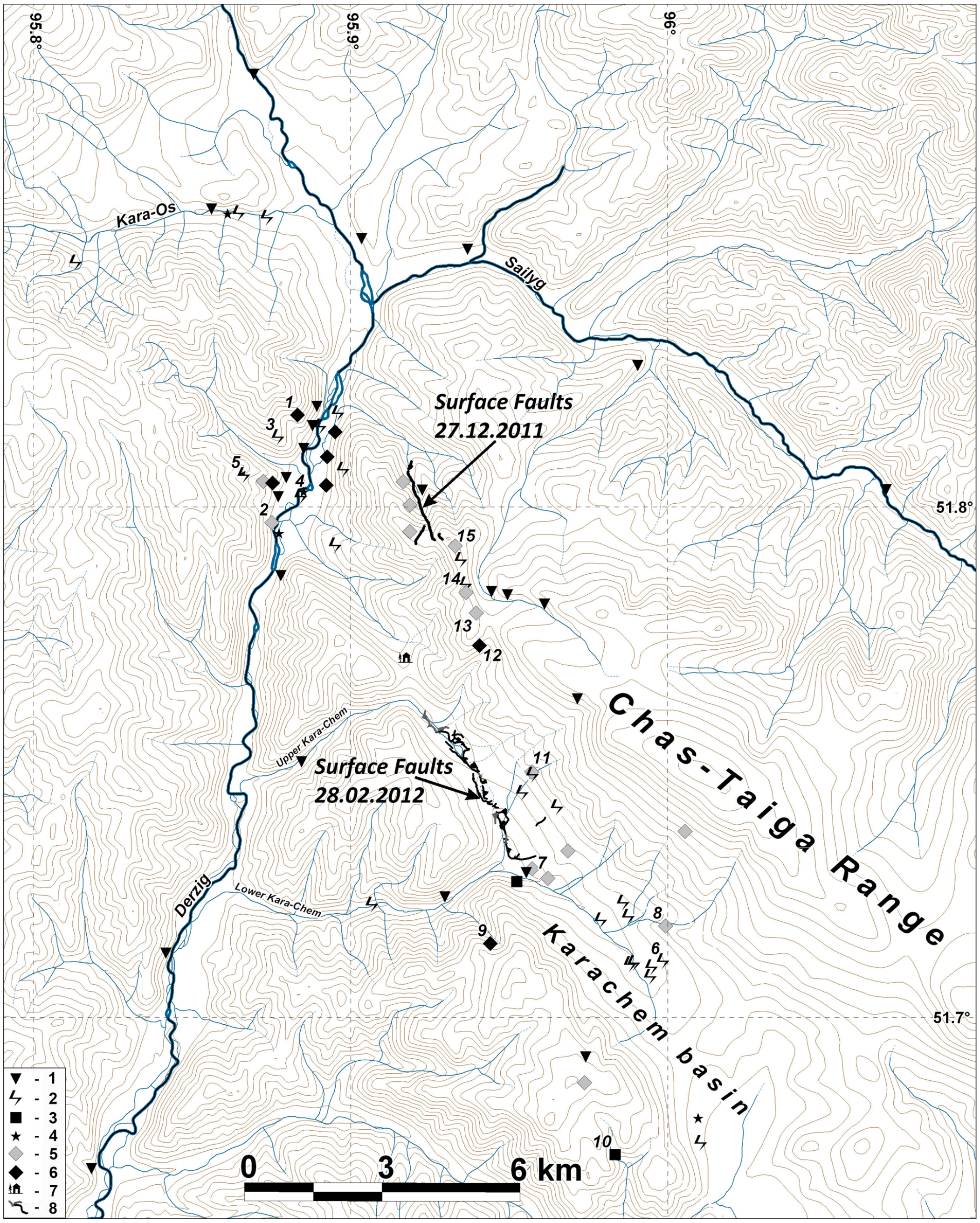

Figure 2. Earthquake environmental effects of the Tuva earthquakes. 1 – screeses and rockfalls; 2 – seismic vibration fracture; 3 – landslides; 4 – sand ejections; 5 – thrown out of the separate blocks; 6 – landfalls; 7 – damaged cottage (izba); 8 – seismic ruptures.

2013, 2015]. The seismic rupture of the second (February) event was discovered and preliminary investigated just in early April of 2012 [*Rogozhin et al.*, 2013]. It is important that study was performed in the winter, before snow melting. This allowed us to get a notion on rupture close to its original form. Already that summer the ruptures were guttered and recognized much more difficult because of thick vegetation.

The displacement mode well correlates with source mechanisms and their position – with coordinates on the instrumental data (with error account) what allows the reliable correlation of the seismic ruptures with specific earthquakes. The seismic ruptures are presented by complex systems of the faults, forming the regular structural parageneses.

The seismic rupture of the first earthquake is arranged relatively simply. It has a north-northwest strike and the right shear displacement kinematics up to 50–60 cm. The amplitude of displacement is determined in several places using

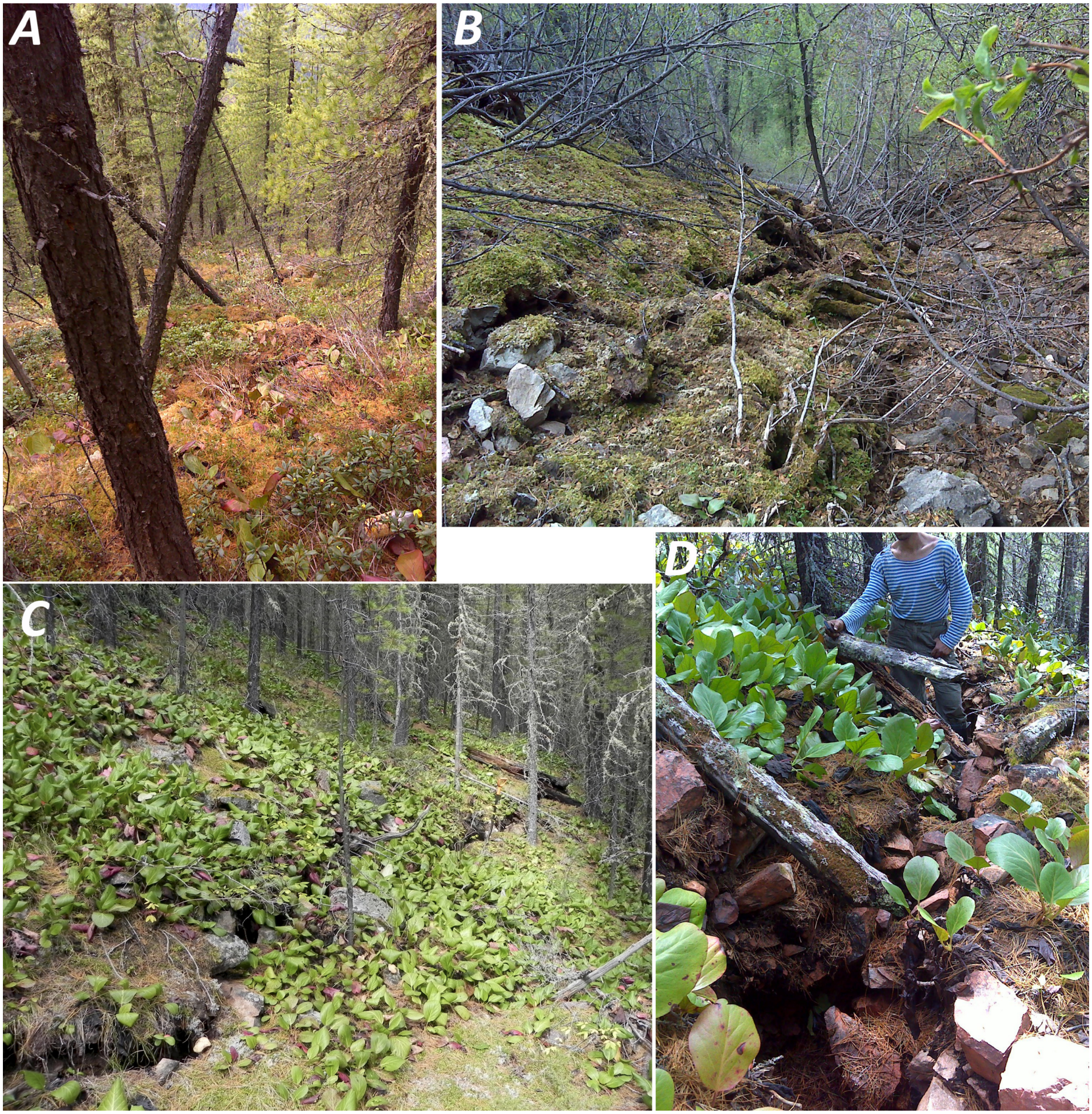

Figure 3. The seismic rupture of the first Tuva earthquake on 27.12.2011. A – "Scouring" strike-slip rupture on the slope of watershed; B – strike-slip rupture in the valley of the stream; C – normal fault – strike-slip rupture on the western limitation of the saddle-graben; D – normal fault – strike-slip rupture on the eastern limitation of the saddle-graben.

the disrupted roots and trunks of lying trees. The length of the rupture is about 1.6 km. Taking into account the short fractures in the near watershed part of ridge, fitting to the common structural ensemble, the length of the fault system is 3.1 km. The ruptures are mainly represented by system of conjugated short stretching cracks and compression swells, forming a "scoured" fracture (Figure 3A). The central segment of seismic rupture ripped the bottom of the stream valley (Figure 3B). Two normal fault-strike slip faults originated on the southern termination of the seismic rupture system (Figure 3C). Between them there is a broad and flat saddle, a football field-like, which contrasts sharply with the surrounding extremely steep slopes. The saddle is a stretching zone on the terminating strike slip, the pull-apart basin

Figure 4. The seismic rupture of the second Tuva earthquake on 26.02.2012. A – upthrust-strike-slip in the valley of the stream, early April, 2012. In the corner is shown the transverse section; B – The upthrust-overthrust, September, 2012. In the corner is shown the transverse section; C – The dextral strike-slip, September, 2012; D – The dextral strike-slip, early April, 2012.

which repeatedly experienced tectonic subsidence under the similar earthquakes.

The seismic rupture of the second Tuva earthquake is more complicated. It stretches north-westward. There are the fractures of practically all the kinematics with three main types. The upthrust-strike-slip faults predominate (Figure 4A). The upthrust-overthrust and strike-slip are less common (Figure 4B, Figure 4C, Figure 4D). Among the latter the left-lateral are dominated although the dextral strike-slips are also found in some spots. The fault systems are mutually connected by gradual transitions, generally forming the regular upthrust-strike-slip structural ensemble of the total length of about 4 km. The maximal horizontal shortening along the rupture is up to 1 m, the vertical displacement – up to 80 cm, the amplitude of the dextral strike-slip – up to 50 cm. On the whole the north-eastern flank of fault with Chas-Tayga ridge appeared to be elevated.

The swamping and flooding of the surface are observed within the sunken flanks of the ruptures with vertical displacements. On the contrary, the dried marsh vegetation

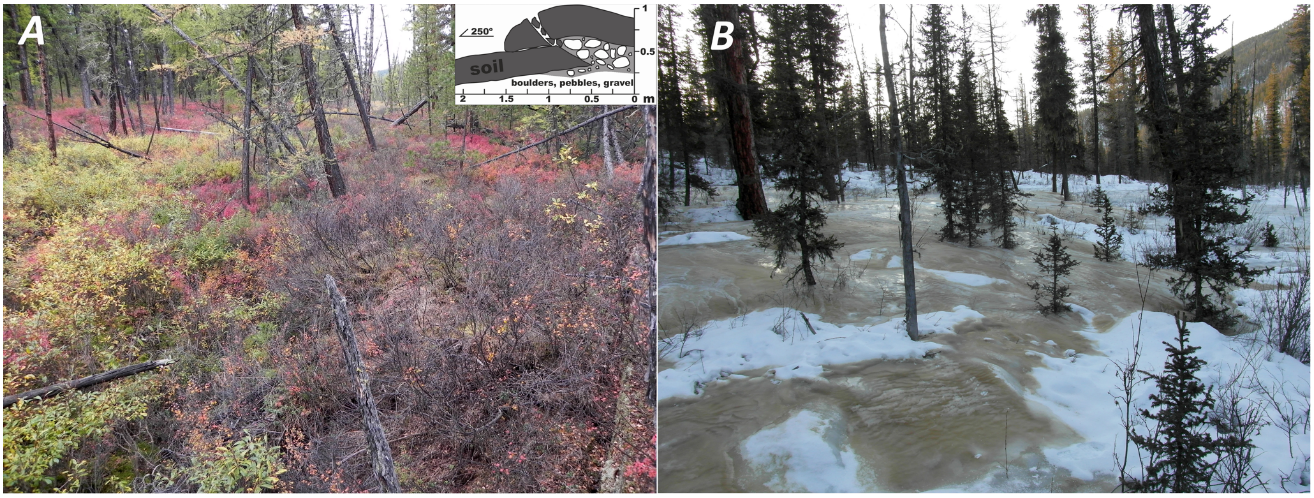

Figure 5. The seismic rupture of the second Tuva earthquake on 26.02.2012. A – The upthrust–overthrust responsible for the elevation and drying of the swamped before land; B – The frazil clogging by sand in the sunken flank of the seismic rupture. Behind the seismotectonic scarp is seen.

is seen on the elevated flanks (Figure 5A). Some swamped lands are situated between separate fault branches, representing the lowered tectonic blocks. The main subsidence occurred in the band of 100–150 m wide along upthrust-strike-slip and upthrust-overthrust faults. The flooding is only partly caused by water from sources originated after earthquake on the elevated flank of seismic rupture. Such sources are formed but on two small spots, while the swamped surface extends as uniform band along seismic rupture. That is why the main cause of flooding is admittedly the tectonic subsidence.

One more bright manifestation of the second Tuva earthquake, connected with exposure of source at the surface, was discovered in the early March, 2012. The unusual, clogging by sand, frazil with striking grayish-brown color, was formed in the upper stream of Lower Kara-Hem, in the sunken flank of the upthrust-strike-slip (Figure 5B). It is most likely a result of the powerful water outpouring from seismic ruptures during the earthquake or immediately after it.

According to ESI 2007 scale the length of the seismic rupture corresponds to the intensity IX. However the amount of displacement suggests the intensity X. The hydrogeological evidences correspond to the intensity IX. So the final assessment may be taken as intensity XI.

4.2. The Secondary Disturbances

The secondary disturbances may be possibly divided into seismic gravitational and seismic vibrational. The seismic gravitational disturbances include landslides, screeses, rockfalls, downfalls, fractures and cracks on the steep slopes as well as rare landslides of the slope cover. In some areas the stones thrown out the cliff are noted. The signs of the emission, outpouring and extrusion of the flooded sand from the cracks in the river floodplains (gryphon) as well as crack forming on the flat surface without gravital strengthening are considered as the seismic vibrational disturbances.

In case of the Tuva earthquakes the determining the identity of the secondary disturbances to the particular event was not possible because the investigation were conducted after both shocks. Thus only their total effect was estimated.

The concentration and sizes of the secondary disturbances are depended on the epicentral distance as well as geologic-geomorphologic pattern. In the epicentral area were most thoroughly examined the several sites which correspond to the abovementioned "points" [*Guerrieri et al.*, 2007; *Tatevossian et al.*, 2009], and where the seismic effect has been estimated by entire set of objects. These are – valley of river Derzig and Kara-Os, Karahem basin and north-western slopes of the ridge Chas-Tayga, where the source of the first earthquake is situated (Figure 2).

The named sites differ in geologic-geomorphologic pattern and position relatively to the earthquake sources. They are the basic landscape units of the region and have the different set of dominated relief forming processes. Just these distinctions determine the predominance of the peculiar disturbance and the extent of their distribution.

Valley of river Derzig. The highest concentration of the seismic gravitational disturbances is observed in the middle flow of Derzig river. The river valley has uneven structure expanding in the tectonic depression and strongly narrowing within elevations. The wide (500–800 m) and flat bottom of the valley usually sharply changes by the steep (30–40°) slopes. The slopes are covered with ancient overgrown collapse-screes rocks and occasional rocky outcrops of solid volcanic and metamorphic sediment of Low-Middle Paleozoic. The meandering riverbed has very rapid current and numerous tributaries, abundant with sandbars, shoals, islands, and filled by boulder-pebble deposits. The morphology of the high floodplain testifies to frequent, up to catastrophic floods, which reach the surface of terraces in the spring and summer. The river regularly overflows on the first hundred meters when snow melting or summer rains.

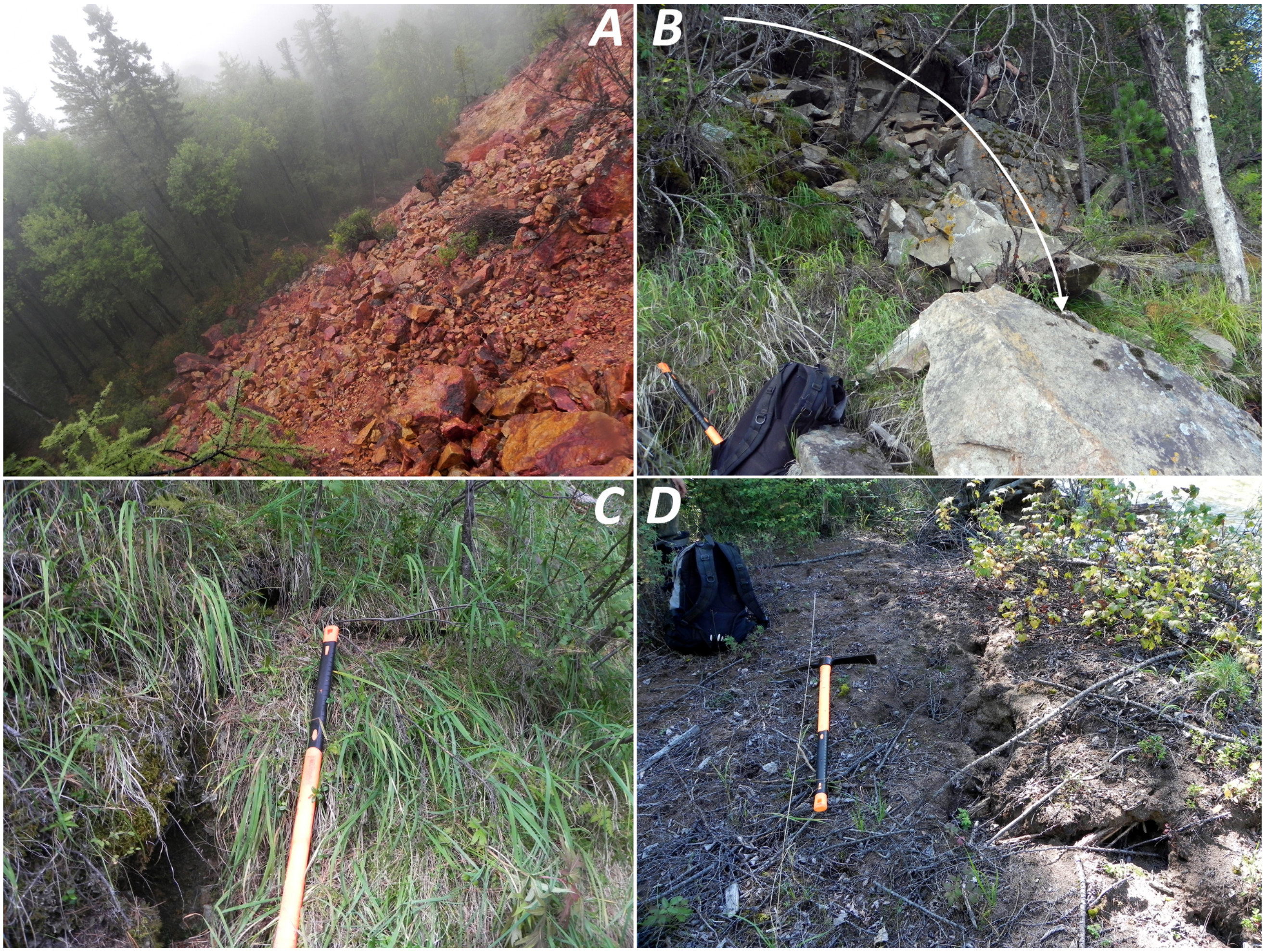

Figure 6. The secondary disturbances in the Derzig river valley. A – the rockfall (1 in Figure 2); B – the thrown from cliff boulder; the arrow shows the direction of its motion (2 in Figure 2); C – the crack of downfall at the valley slope (3 in Figure 2); D – the crack with traces of the thrown sand at the river bottom (4 in Figure 2).

Spring river spill occurred in 2012, too. Erosion and sandy-clay sediments, covered the floodplain, strongly masked the traces of the seismic vibrational effects of the earthquakes.

In result of the earthquakes the slopes of the Derzig valley in the investigated area were covered by collapses and rockfalls. The rockfalls are torn from the cliff walls or from the old forested landslide cones. The rockfall bodies consist of the large blocks (up to 4 m across), typically at some distance from valley boards. On the crests of ridges in the valley boards there are a lot of twisted counterclockwise and broken trees at a high of 1.5–3 m. All the cliff outcrops are severely cracked and covered with stones dislodged from the cliff and serve as source of rockfalls and small collapses. The thrown stones are not more than 0.5 m across, at the distance not more than 1 m.

In one case the large collapse of about 40,000 m^3 was found (Figure 6A). It consists of large (up to 2 m in diameter) boulders of the brown, fractured, strongly altered early Devonian porphyrite and quartzite which cover coat-like the steep bare slope. It came from the western part of the separation wall of ancient landslides destroying it completely. The separation wall is of regular circus-like shape with height of about 13 m and about 80 m wide. During the one of the winter earthquake, 2011–2012, the 1.5–2.0 m displacement of the landslide took place.

The rockfalls are often marked by signs of the anomalous horizontal displacement. The boulder accumulation is noted at the right board of river – these boulders obviously were split off from the vertical rocky cliffs and horizontally displaced at distance 7–8 m. The largest boulder of 2×4 m in size was thrown from cliff at distance about 4 m considering the lack of the dents on the slope and its position respectively to the separation niche (Figure 6B).

Apart from rockfalls, the river slopes are struck by numerous downfall fractures. The fractures have the zigzag-like shape with sharp corners that points to their originating in the hard frozen soils (Figure 6C). The width of the fractures is up to 50 cm, the length – up to 10 m.

At the right board of Derzig river there is valley of the small stream with steep (20–35°) slopes and V-like cross-

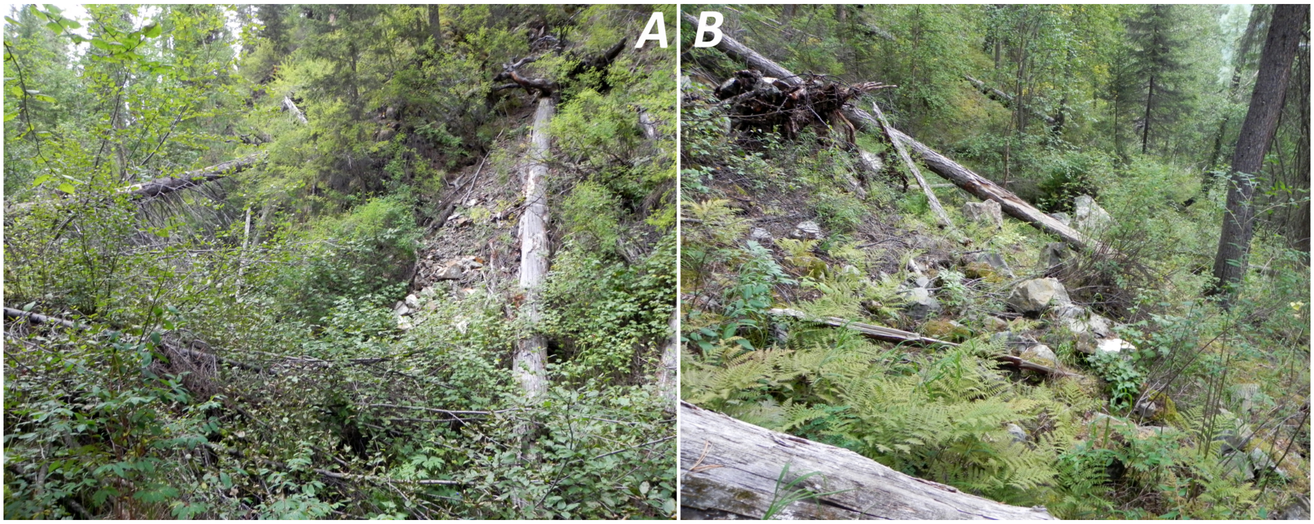

Figure 7. The secondary disturbances in the right board of the Derzig river valley (5 in Figure 2). A – the common view; B – the rockfall at the foot of the valley slope.

section. It is almost completely filled up with trees and stones (Figure 7). The slopes are covered with numerous small (about 8 m in diameter) landslides, downfall fractures and fallen trees. The bottom of valley and stream channel are overwhelmed with broken trees and stones from the slopes. The boulder of 1 m in size was thrown at horizontal distance about 10 m. In the valley bottom, along the channel incision, the band of the fractures of downfall stretches, its length is about 200 m. As a result the boards of the channel incision turned out to be almost completely bare while the cover was thrown and replaced into the stream channel.

At the edge of the floodplain terrace of Derzig river are noted some open downfall fractures of 15 cm wide and 10 m long. Along the cracks near the river bottom the sand is preserved which was likely thrown during the one of the earthquakes (Figure 6D). This testifies to that in winter of 2011–2012 the river sediments were not completely frozen and possessed the water. The cracks, situated farther from the river bottom, have the straight edges and sharp corners what means the soil cracking in the frozen state.

The forming cracks of 10 cm wide in the solid soils corresponds to the intensity IX according to the ESI 2007 scale. Since the frozen soil is absent in the ESI 2007 scale it may be possible to estimate the described effect as similar to the solid soil with intensity IX. The thrown boulders, though less certainly due some inconsistencies in ESI 2007 scale, correspond to the intensity IX. The rest of the effects correspond to the less intensity: VII–VIII for the rockfall in the point 1; VII – for the sandy fractures in the Derzig valley. Regarding the abovementioned peculiarities of the ESI 2007 scale as well as the very high concentration of the secondary effects the intensity IX is taken for investigated part of the river Derzig valley.

Karahem Depression. Karahem depression accommodating the upper reaches of the Upper and Lower Kara-Hem streams represent the specific neotectonic form. The width of depression narrowed north-westward from 2.5 up to 0.4 km. Being the young tectonic unit it is characterized by small erosion incision and wide swamped bottoms of the streams with meandered channels. Beyond the depression the erosion incision sharply increases and the stream channel possess the canyon-like shape. The depression stretches along the Kaahem fault which is the boundary of the various igneous rocks (granitite and granodiorites) of different age. The fault zone is of 1–2 km wide, i.e. it occupies almost all bottom of the depression. The north-eastern board is cut off by young tectonic scarp along which Chas-Tayga ridge is thrown at the depression. The main part of depression is occupied by gently inclined (5–10°) surfaces of the proluvial foothill plumes consisting of the boulders and rubbles of granitoids and in less extent – sandy-clay sediments. In addition to the seismic rupture there are discovered the bright secondary disturbances.

The seismic vibrational fractures are mostly widespread at the surface of the foothill trail. The obvious sizes of fractures are 10–30 (up to 0.8) cm wide and 10–15 m (up to 30 m) long. The fractures are observed both in the coarse clastic soils of the proluvial trails (Figure 8A) and in the sandy-clay sediments of streams.

The small collapses, screeses, rockfalls and landslides not exceeding 30,000 m^3 occurred on the output of the Lower and Upper Kara-Hem streams from depression and at the slopes of Chas-Tayga ridge (Figure 8B, Figure 8C, Figure 8D).

In the south-eastern part of depression, about 3 km from seismic rupture (8 in Figure 2), the knocked boulder of 1 × 0.8 m in size flew at 2 m. Here, the smaller boulder (0.8 × 0.6 m) flew at 3 m. In this case the direction of the thrown out is clearly established – to the South-East, i.e. in the opposite side from seismic rupture.

One of the brightest secondary effect illustrating the direction of the seismic shock is discovered at the elevated flank of the tectonic scarp along foothill of the Chas-Tayga ridge

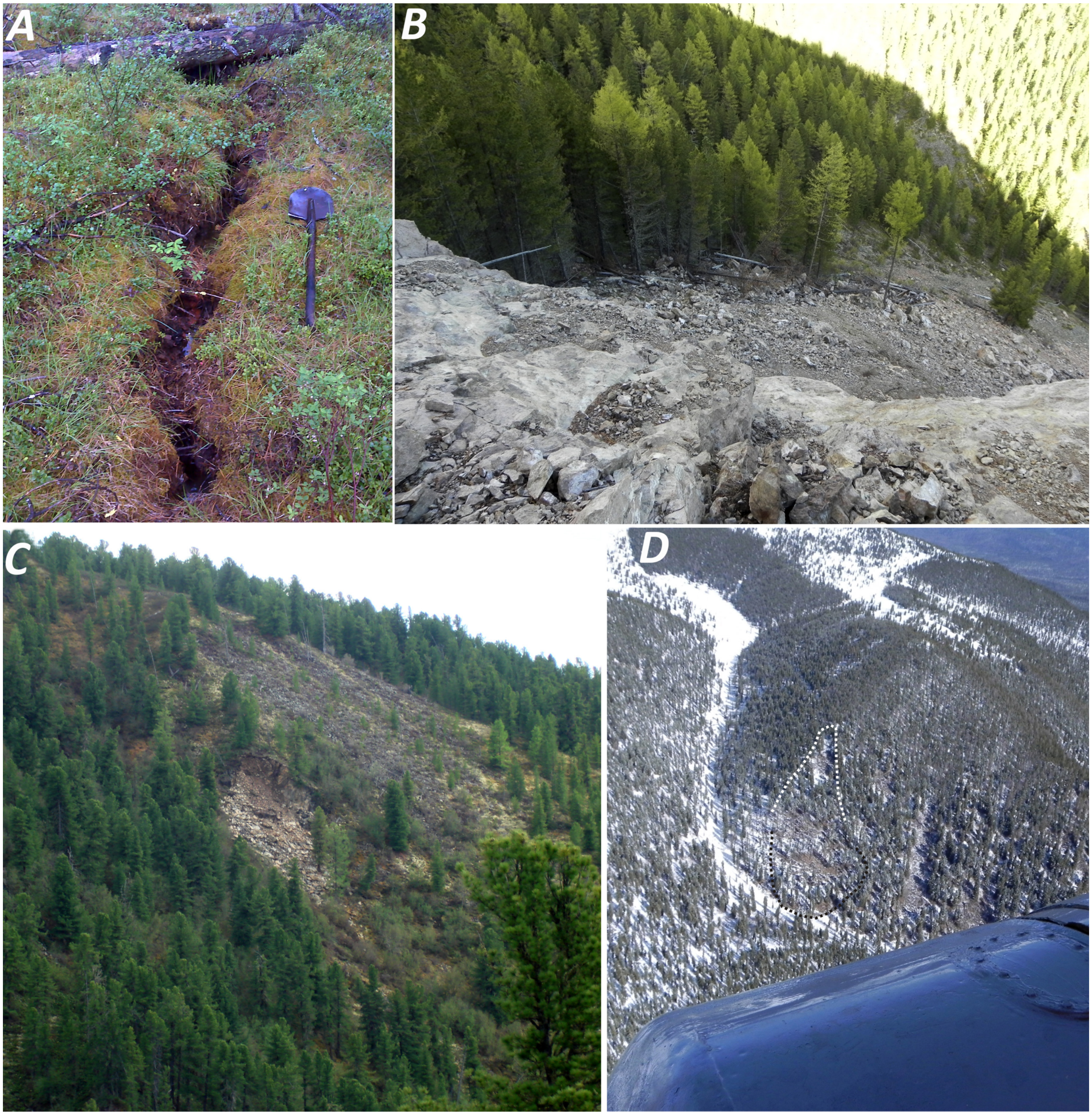

Figure 8. The secondary disturbances of Karahem depression and its vicinity. A – the vibrational fracture in the rocky ground of the proluvial trail (6 in Figure 2); B – the rockfall at the slope of the Chas-Tayga ridge (12 in Figure 2); C – the rockfall at the slope of the watershed (9 in Figure 2); D – the slideslip of the slope cover (10 in Figure 2).

(Figure 9). In 10 km north-westward from the scarp the stream valley cuts the granitoids forming the canyon with vertical rocky boards. Here, in the rhombic separation niche of the old rockfall, connected with fracture in granitoide, has occurred the thrown out of the stones. The largest from the preserved boulder is of 1.5×3 m in size. Next to it are somewhat smaller stones (0.5×0.3 m). The piece of rock flew out in the horizontal direction at about 5 m, hit the opposite side of niche (there is the only dent) and jumped from scarp for another 4 m. The northeastern thrown out trend is oriented in opposite side from seismic rupture.

In the framing of the Karahem depression the rockfalls and screeses emerged not only at the slopes of the Upper and Lower Kara-Hem stream valleys. Between them, on the

Figure 9. The thrown out stones from rockfall niche (11 in Figure 2). The arrow shows the relocation of the biggest boulder.

gentle watershed, the thrown stones and cracked outcrops were noted. Most reliable distance of thrown out is 1 m for the boulder of 1×0.7 m (13 in Figure 2). The thrown out had southern trend, in opposite side from seismic rupture.

The distribution of the secondary effects is governed by remarcable regularity. The majority of them occurred to the South-west from tectonic scarp along the foothill of Chas-Tayga ridge. Some of them are situated immediately near the scarp what partly is caused by contrast geomorphology. North-eastward from the scarp but a few effects is marked despite the increasing steepness of the slopes. It suggests most likely to the zone of the attenuation of the seismic wave connecting with active fault.

The average estimate of intensity on the seismic rupture parameters in Karahem depression is IX. It correlates with estimates on the fracture sizes (with account to the frozen soil) and thrown stones. However the amount of the rockfalls and landslides is not correlated with intensity IX.

The North-Western Slopes of the Chas-Tayga Ridge. This area is directly connected with the source of the first earthquake. The apical part of the Chas-Tayga ridge has very gentle shape. At 1850–2000 m and higher the apical surfaces are covered by stone placers and mountain tundra, below – taiga. In the North-West it stepped and ends up with the steep slopes of the river Derzig valley.

The most significant effects are marked on the flat apical surface of the small spur of Chas-Tayga ridge.

There are the numerous thrown stones increasing in size northward with nearing to the seismic rupture of the first earthquake. Thus, the size of the biggest stone in the point 13 is 0.5×0.7 m and distance of thrown out – 1 m while in the point 15 the flat plate of 1.5×2 m was cracked in half and both fragments were thrown at the distance 3 m. The predominant trend of stone thrown out is South-East, i.e. in opposite side from seismic rupture of the first earthquake.

On the surface of the same spur there are differently oriented vibrational fractures of 300 m long and 40 cm wide (Figure 10A). On the slopes of the watershed the gravitational downfall up to 0.8 m is observed (Figure 10B).

The numerous thrown stones and small screeses are also observed at the steep slopes of the valley stream in the bottom of which the seismic rupture of the second Tuva earthquake is traced. The size of the thrown stones is no more 1 m.

The described effects on the ESI 2007 scale correspond generally to intensity IX.

The River Kara-Os Valley. The river bottom within a plot of about 6.4 km is dug by gold miners. The foots of the vertical rocky walls on the left board are covered by old stabilized collapse cones. In the slope foot there is a small fresh screeses. During the earthquake the rockfalls were torn from ancient downfall walls. In one case the throwing the small stones (up to 0.5 m in diameter) over the river took place, i.e. the stones were thrown from cliff at distance about 10 m in horizontal direction. The surface of the gold mining is covered by seismic vibrational fractures up to 150 m long and 40 cm wide. In the lowering of the excavation, i.e. near the water level, the numerous traces of the liquefied sand discharge are marked (Figure 11). They are represented by sand cones of 1.5 m in diameter.

The described effects on the ESI 2007 scale correspond to intensity VIII.

5. Damage of Building

In the epicentral area the only seriously damaged cottage (izba) was fixed on the watershed saddle between the right tributary of Derzig river and upper flow of the Upper Kara-Hem stream (Figure 12). The izba of size 2×2 m, built two-four years ago, turned out to be skewed. The bars shifted to North-west at 10–15 cm. The main shift occurred near the base, in the second bar from below. The young cedar (about 10 cm thick) fell at the izba, it was broken at the height 4 m, and falling, broke the roof. Such damage

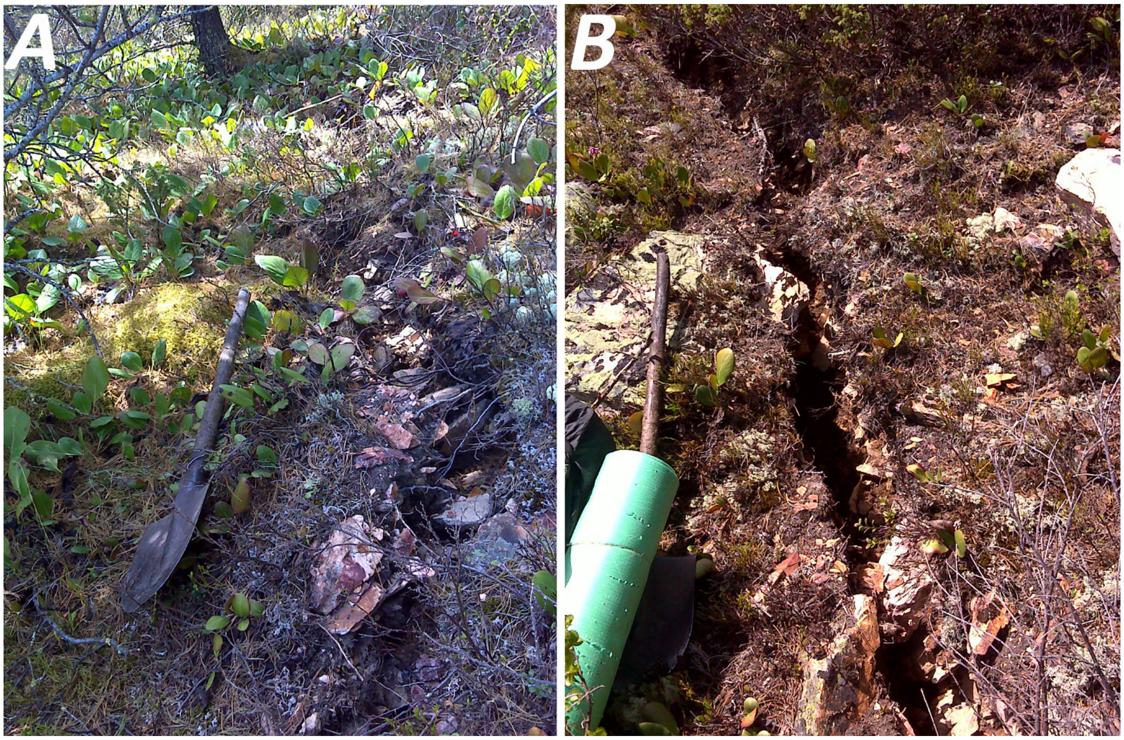

Figure 10. The secondary disturbance in the source of the second Tuva earthquake. A – the downfall fracture in the rocky soil (14 in Figure 2); B – the open vibrational fracture in the rocky soil (15 in Figure 2).

corresponds to the intensity IX on the MSK scale. It is of interest that bars were displaced in the opposite site from the seismic rupture of the second earthquake.

One more izba, in 130 m from seismic rupture of the second earthquake has no serious damage. It was built many years ago on the surface of the coarse piedmont rock, not far from Lower Kara-Hem stream. Unusually weak destructions in the immediate vicinity from seismic rupture were noted repeatedly under the study of various earthquakes.

One of the most striking examples – the catastrophic Venchuan earthquake of 2008 in China. Here, in vicinity of the seismic rupture, the macroseismic effect turned out to be anomalously low – intensity about VII–VIII on the scale MSK comparing with intensity XI following from the seismic ruptures [*Rogozhin, Shen*, 2011]. The exception were the construction which were directly ripped by seismic rupture whereas a few meter from it even glass survived in the building.

Figure 11. The secondary disturbance in the bulking alluvium in the river Kara-Os valley.

Figure 12. The skewed izba.

6. Discussion of the Result

The map of intensity isolines in the near zone was compiled from results of intensity assessment (Figure 13). The shown intensity isolines are the conventional lines very approximately limiting the areas with different concentration of the secondary disturbance. The considerable uncertainty of the obtained result depends also on the only total effect of shocks from the two seismic events.

In general, the secondary disturbances occurred within some relatively small areas with favorable landscape-geomorphologic condition. In the epicentral area the numerous stones, thrown upward or horizontally from cliff are fixed. According to the ESI 2007 scale the stone throwing corresponds to the intensity VIII or IX, most definitely – IX. At a distance from the seismic ruptures in the few hundred meters (300–400) and more somewhere the throwing direction is well determined. As a rule it is oriented in opposite site from seismic ruptures. In the vicinity of the seismic ruptures the direction of the boulder thrown out does not reveal any consistent trend. The sizes of the vibrational fractures also correlate with intensity IX however with account to their originating in the frozen soil, i.e. in the solid substrata. In the area of the maximal shock the sizes of the rockfalls and landslides (VII–VIII degrees) are not consistent with intensity IX.

One peculiarity is noted in the distribution of the secondary effects. The vast majority of them occurred southwestward from the tectonic scarp along the foothill of the Chas-Tayga ridge. Many disturbances occurred immediately near the scarp what is partly connected with contrasting geomorphology. To the North-East from the scarp, despite the sharp increasing steepness of the slopes, the only a few effects are marked. Most likely it may suggest to the zone of attenuation of the seismic waves associated with active tectonic fault.

The total area of the systematic manifestation of the secondary disturbances is about 900 km^2. In accordance with recommendations of ESI 2007 scale the separate isolated effects in the far zone are not included. The area of the secondary disturbance distribution as a whole correlates with intensity IX (approximately 1000 m^2).

The seismic ruptures, as a rule, have originated on the limitation of the small morpho-structures – for example, shaft-elevation in the bottom of the Karahem depression or some graben-saddle in the zone of the first earthquake. They divide the spots with sharply different geomorphology. In general the displacement along the faults reflects the development trend of the morpho-structures traced during the Late Pleistocene–Holocene. These primarily relate to the shortening the Karahem depression resulted from contracting in the Kaahem fault zone as well as some local subsidence.

The distinctive pattern of the seismic ruptures is their small length comparing to the event magnitude. The length of the seismic ruptures corresponds to the intensity IX on the ESI 2007 scale. However the amount of displacement testifies to the intensity X. The hydrogeological manifestation along the seismic rupture of the second earthquake corresponds to intensity VIII–IX. Although in the strip of about 600–800 m wide along the seismic rupture the effects of the strong shocks were not observed. The izba situated in this strip has no serious damage. The seismic vibrational fractures are absent, too, despite to the favorable condition (the swamped stream valleys). The major damage in this strip is associated with seismotectonic ruptures. This is not only

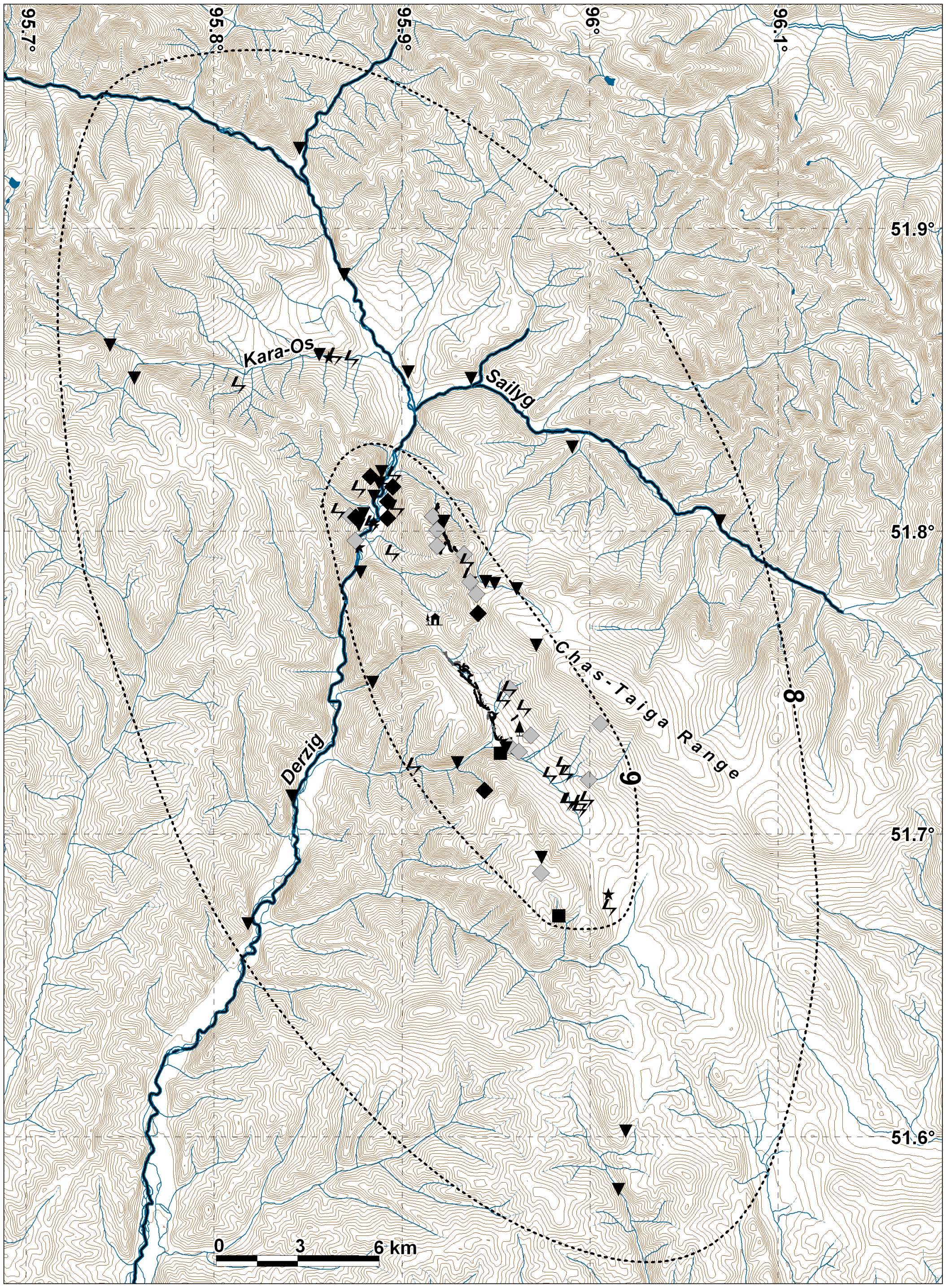

Figure 13. 8 and 9 intensity isolines in the near zone of the Tuva earthquakes.

contradiction in the ESI 2007 scale. The scale also does not consider the difference between the frozen and unfrozen soils, between winter and summer condition what is essential for the Siberian mountain. Obviously the earthquake manifestation would be strongly changeable depending on these factors in the sharpl continental climate of Siberia.

7. Conclusion

The paper considers the primary and secondary environmental effects resulted from two Tuva earthquake in 2011–2012. The field study of these effects conducted soon after earthquakes enable us to obtain the valuable information on the manifestation of occurred strong seismic events. The seismic ruptures were traced on the surface and studied in detail what is of importance for this poorly investigated region. The seismic ruptures have the peculiar feature associating most likely with specific geologic-geomorphological pattern of region as well as soil character. Thus, the seismic ruptures of both earthquakes differ in their parameters in term of kinematics and size. The specific "scouring" rupture is distinguished for the first earthquake what clearly demonstrate the changeable geologic-geomorphological situation where seismic rupture "navigates his way". The remarkable is also the discrepancy between size of the ruptures and displacement along them what does not let the unambiqous definition of magnitude without using the secondary effects.

The investigation of the secondary effects revealed their rich variety in this region, largely exceeding the set of such manifestation given in the ESI 2007 scale. That is why authors had to adapt the ESI 2007 scale to the obtained data and forced to use the analogue. The best example – the absent frozen soil in the ESI 2007 scale, though there are the other too.

Nevertheless our work was attempted to apply the ESI 2007 scale for the Siberian mountains studying the fresh traces of the recent events. The traces are clearly divided into two groups: the second ones resulted from seismic shocks and primary immediately reflected the earthquake source at the surface as seismic rupture. The distinctive feature of the both earthquakes is the small length of the rupture comparing to magnitude. The secondary disturbances are represented by rockfalls, screeses, downfall fractures on the steep slope, rare landslides of the slope cover and fractures with watered sand ejections in the floodplain of the big rivers. The collected data on the distribution of the secondary effects of the earthquakes allowed us to outline in general the areas with VIII and IX-intensities. There is a strip of about 600–800 m wide where the signs of the strong seismic shocks are almost absent.

While using the ESI 2007 scale some peculiarities were revealed which cause the difficulties of its application in the Siberian mountains. The scale does not consider the difference between the frozen and unfrozen soils, between winter and summer condition. Despite this the use of the scale allows the obtaining a large amount of the new data on the assessment of the effect of the strong seismic events. Such the data is a base for the seismic hazard assessment of the whole Altay-Sayan region.

Acknowledgments. The authors heartily thank the Head of the Department of the Civil Defence of the Ministry of Emergent Situations RF S. L. Didenko for assistance in arranging the helicopter flight over the epicentral zone of the Tuva earthquakes. The work was supported by RFFI (grants 14-05-00091, 15-45-04351, 15-35-50401).

References

Arzhannikov, S. G. (2000), Paleoseismic dislocations in the Ottugtaiginsko-Azassky fault zone (Eastern Tuva), *Russian Geology and Geophysics*, *41,* No. 11, 1499–1504.

Arzhannikov, S. G., P. Ya. Zelenkov (1995), Strong Paleoearthquakes of Akademik Obruchev Range (Eastern Tuva), *Seismicity and Seismic Zoning of Northern Eurasia, No. 2/3* p. 323–330, UIPE RAS, Moscow. (in Russian)

Baljinnyam, I., et al. (1993), Ruptures of major earthquakes and active deformation in Mongolia and its surroundings, *Geological Society of America*, *181,* 62. doi:10.1130/MEM181-p1

Berzhinsky, Yu. A., et al. (2010), Application of the ESI-2007 Scale for Estimating the Intensity of the Kultuk Earthquake, August 27 2008 (South Baikal), *Seismic Instruments*, *46,* No. 4, 307–324. doi:10.3103/S0747923910040018

Chernov, G. A. (1978), Seismogeological and neotectonic studies in the Altai-Sayan area, *Seismogeology of the Eastern Altai–Sayan Mountain Area (Solonenko V. P., Nikolaev V. A., eds.)* p. 6–27, Nauka, Novosibirsk. (in Russian)

Emanov, A. F., A. A. Emanov, E. V. Leskova, V. S. Seleznev, A. V. Fateyev (2014), The Tuva earthquakes of December 27, 2011, $ML = 6.7$, and February 26, 2012, $ML = 6.8$, and their aftershocks, *Doklady Earth Sciences*, *456,* No. 1, 594–597. doi:10.1134/S1028334X14050249

Ivanovsky, L. N., V. B. Vyrkin (2006), Geomorphological research in Siberia, *Geography of Siberia* p. 37–43, Research India Publications, Delhi.

Goldin, S. V., O. A. Kuchai (2007), Seismic strain in the Altai-Sayan active seismic area and elements of collisional geodinamics, *Russian Geology and Geophysics*, *48,* No. 7, 536–557. doi:10.1016/j.rgg.2007.06.005

Guerrieri, L., R. Tatevossian, E. Vittori, V. Commerci, E. Esposito, A. M. Michetti, S. Porfido, L. Serva (2007), Earthquake environmental effects (EEE) and intensity assessment: the INQUA scale project, *Boll. Soc. Geol. It.*, *126,* No. 2, 375–386.

Kudryavtsev, G. A., V. A. Kuznetsov, (Eds.) (1966), *Geology of the USSR. Tuva ASSR, part 1 (Geology Description), vol. 29*, 459 pp., Nedra, Moscow. (In Russian)

McCalpin, J. P., (Ed.) (2009), *Paleoseismology, 2nd Edition*, 647 pp., Elsevier Publishing, Amsterdam–London.

Michetti, A. M., et al. (2004), The INQUA scale. An innovative approach for assessing earthquake intensities based on seismically induced ground effects in natural environment, *Special paper APAT, Memorie descritive della carta geologica d'Italia*, *67,* 118.

Michetti, A. M., et al. (2007), Intensity scale ESI 2007, *Special paper APAT, Memorie descritive della carta geologica d'Italia*, *74,* 41.

Ovsyuchenko, A. N., A. V. Marakhanov, R. N. Vakarchuk, A. S. Larkov, S. S. Novikov, E. A. Rogozhin (2013), Geological and macroseismic manifestations of the earthquake on October 16, 2011 in the Skovorodino region, Amur oblast, *Seismic Instruments*, *49,* No. 4, 315–327. doi:10.3103/S0747923913040051

Rogozhin, E. A., X. Shen (2011), The seismotectonic and macroseismic features of the Wenchuan (Sichuan) earthquake ($Ms = 8.0$) of May 12, 2008, *Seismic Instruments*, *47,* No. 2, 167–179. doi:10.3103/S0747923911020083

Rogozhin, E. A., A. N. Ovsyuchenko, A. V. Marakhanov, A. S. Larkov, S. S. Novikov (2013), Tectonic position and preliminary data on geological manifestations of the 2011–2012 Tuva earthquakes, *Seismic Instruments*, *49,* No. 2, 178–187. doi:10.3103/S0747923913020023

Rogozhin, E. A., A. N. Ovsyuchenko, A. V. Marakhanov, S. S. Novikov, A. S. Larkov (2015), Geological Manifestations of the 2011–2012 Tuva Earthquakes, *Doklady Earth Sciences*, *462,* No. 1, 728–732. doi:10.1134/S1028334X15070144

Serva, L., et al. (2016), Earthquake Hazard and the Environmental Seismic Intensity (ESI) Scale, *Pure and Applied*

Geophysics, *173,* No. 5, 1479–1515. doi:10.1007/s00024-015-1177-8

Tatevossian, R. E. (2007), The Verny, 1887, Earthquake in Central Asia: Application of the INQUA Scale, Based on Coseismic Environmental Effects, *Quaternary International*, *173–174,* 23–29. doi:10.1016/j.quaint.2007.02.006

Tatevossian, R. E., et al. (2009), Earthquake intensity assessment based on environmental effects: principles and case studies, *Geological Society London, Special Publications*, *316,* 73–91. doi:10.3103/S0747923910020052

Tatevossian, R. E., N. G. Mokrushina, A. N. Ovsyuchenko, T. N. Tatevossian (2010), Geological and Macroseismic Effects of the Muya, 1957 Earthquake and Paleoearthquakes in Baikal Region, *Seismic Instruments*, *46,* No. 2, 152–176.

Zhalkovsky, N. D., O. A. Kuchai, V. I. Muchnaya (1995), Seismicity and some characteristics of the state of stress of the Earth's crust in the Altai–Sayan region, *Russian Geology and Geophysics*, *36,* No. 10, 16–25.

A. S. Larkov, A. V. Marakhanov, S. S. Novikov, A. N. Ovsyuchenko, E. A. Rogozhin, Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, 10 B. Gruzinskaya, 123242 Moscow, Russia (ovs@ifz.ru)

Yu. V. Butanaev, Tuva Institute for Exploration of Natural Resources, Siberian Branch of the Russian Academy of Sciences, Internatsionalnaya 117a, Kyzyl, 667007, Russia