Large earthquakes in the Katun Fault zone (Gorny Altai): Paleoseismological and archaeoseismological evidence

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A R T I C L E   I N F O

Article history:
Received 13 February 2018
Received in revised form 15 October 2018
Accepted 8 November 2018

Keywords:
Paleoearthquake
Seismites
Burial mound
Iron age
Late Pleistocene
Holocene
Katun fault
Gorny Altai

A B S T R A C T

Paleoseismological and archaeoseismological research in the Katun Fault zone in Gorny Altai reveals soft-sediment deformation structures (SSDS) in Late Quaternary sediments that fill the Yaloman graben. SSDS (seismites) were produced by large paleoearthquakes (M ≥ 5.5) along the Katun Fault that occurred about 150 and 90 ka, in the 38–19 and 19–12.5 ka intervals, and after 12.5 ka. The event after 12.5 ka within the graben had a magnitude of M s = 7.2–7.6. Traces of another event, shaking intensity I = V (ESI 2007 intensity scale), timed in the range from the 3rd century BC to the 1st century AD, were discovered during studies of a Scythian necropolis at the Chultukov Log 1 site located within the Manzherok graben in the northern end of the Katun Fault. Burial mounds near a mountain slope at the site are damaged by colluvium. Rocks of the same colluvium are scattered over 25 m off the slope and deform burial structures (cairns and stone rings, and inner stone walls of grave chambers), as well as the primary anatomical position of buried bodies, including those in burials not damaged by colluvium from outside. Thus, the Katun Fault was an active structure generating large earthquakes from the Middle Pleistocene through the Holocene.

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1. Introduction

The Altai mountainous system is situated in the northern part of the Central-Asian mobile belt. Its Cenozoic structures inherit those of the western branch of the Altai-Sayan fold system in the region of Russia, Mongolia, China, and Kazakhstan (Delvaux et al., 2013). The ranges of the Gorny Altai (Siberian Altai) are the northern continuation of the Mongolian and Gobi Altai structures (Fig. 1a).

Judging by data of instrumental seismicity and evidence of historic events rarely exceeding M = 5–6 (Fig. 1b), the Gorny Altai was considered less active than the neighbouring areas of Mongolia, the Baikal rift, and the Tien Shan. However, this view changed after the M w = 7.3 (I = 8–9) Chuya earthquake of 27 September 2003 that occurred at the junction between the Chuya and Kurai basins and was followed by numerous aftershocks, some M ≥ 5 (Leskova and Emanov, 2013). The seismic risk map of the Russian Federation (Ulomov et al., 2016), in its latest version, shows active faults within the Gorny Altai region which can generate up to M = 7.0–7.5 earthquakes, with a predicted shaking intensity of I ≥ VIII-IX. However, these predictions lack any solid background of historic and instrumental seismicity records for the past 250 years. Paleoseismology can provide more reliable reference for seismic risk division, but the available data on surface ruptures from large past events are restricted to the South Terekta, South Chuya, Kurai, and Kubadru faults (Fig. 1b) (Rogozhin et al., 2008; Deev et al., 2013, 2017, 2018).
Fig. 1. Location map of the Gorny Altai and study area in the framework of Central Asia (a) after Deev et al. (2017). Active faults are shown according to Trifonov et al. (2002), Cunningham (2007), and Yang et al. (2008). GPS-derived velocities in mm year$^{-1}$ (numerals in 95% confidence ellipses) with respect to Eurasia are from Calais et al. (2003). Historical and instrumental earthquakes are from Kondorskaya and Shebalin (1977), Kal'metjeva et al. (2009), and Radziminovich et al. (2016). Main active faults of the study region are after Trifonov et al. (2002), Rogozhin et al. (2008), Deev et al. (2013, 2017), and Ulomov et al. (2016) (b). Circles show historical and instrumental earthquakes from IRIS seismic catalog and from Ulomov and Medvedeva (2011). Base map was compiled using GeoMapApp (http://www.geomapapp.org).
while the seismic potential of other faults remains poorly constrained.

One of these insufficiently studied structures is the ~200 km long active Katun fault, which according to (Ulomov et al., 2016) could be linked to earthquakes with $M = 7.0$–$7.5$. However, the known instrumental events recorded in the 60s of last century and related to the fault are mostly small or moderate (several tenths of $M = 3.0$–$4.0$ earthquakes) and few are relatively large (three $M = 4.1$–$5.0$ and one $M = 6.0$ shock) (Fig. 1b, Fig. 2). These data are clearly not enough to analyze the seismic mode and for a reliable estimate of the seismic hazard of the territories adjacent to the fault. Consequently, one of the most important goals is to complement the catalogue of strong earthquakes for a wider age interval. The only reliable source of information on the position of epicenter zones, magnitudes, ages and repetition periods of strong earthquakes are data of paleoseismology and archaeoseismology. Below we report the results of our new studies of earthquake-induced soft-sediment deformation structures (SSDS) in Quaternary sections of the Yaloman Basin, with a focus on stratification, spatial correlation, and AMS $^{14}$C, OSL, and IR-OSL isotope dating of the deformed beds. We also present results of investigations of damage to the mounds of the Chultukov Log 1 necropolis that appeared due to a strong paleoearthquake. This research is of special importance as the valley of the Katun River that drains the fault is densely populated and is currently an area of rapid tourist development and a possible pathway for a future gas pipeline to China.

![Fig. 2. Yaloman Basin. White lines are active faults. Historical and instrumental earthquakes are according to data of the Altai–Sayan Department of the Geophysical Service of the Russian Academy of Sciences (from 1963 to 2009), the IRIS seismic catalog, and Ulomov and Medvedeva (2011).](image-url)
2. Regional setting

2.1. Regional tectonics and active faulting

The Cenozoic intracontinental orogen of Altai mountains (Fig. 1a) formed as a far-field effect of the India-Eurasia collision (Molnar and Tapponnier, 1975; Le Pichon et al., 1992; Dobretsov et al., 1996; Yin, 2010). Orogeny in Gorny Altai, in the northern part of the orogen, began in the Paleocene and culminated in the Quaternary (Fedak et al., 2011; Deev et al., 2012a; Glorie et al., 2012). Cenozoic crustal deformation led to growth of mountains as high as 4.5 km a.s.l., with more than 5.5 km of structural relief, which corresponds to displacement of the preorogenic erosion surface up to 1–4 km at junctions between mountains and large intermontane basins (Chuya, Kurai, Uimon, etc.). Vertical displacements of smaller blocks from kilometers to tens of kilometers reach several tens to hundreds of meters (Deev et al., 1995, 2012b, 2013; Rusanov et al., 2013, 2017; Nevedrova et al., 2014). Ongoing crustal movements can be identified by the Global Positioning System (GPS) network and geodetic levelling (Kolmogorova and Kolmogorov, 2002; Timofeev et al., 2006, 2014). A significant role in the tectonic framework of Gorny Altai (Fig. 1b) belongs to strike-slip, reverse, and oblique-slip faults (Lukina, 1996; Trifonov et al., 2002; Cunningham, 2007; Chikov et al., 2008, 2012; Delvaux et al., 2013; Nevedrova et al., 2014), though the slip geometry remains unconstrained for many faults.

One of the long and active faults of the Gorny Altai is the Katun Fault (Fig. 1b). The history of the fault began in the Quaternary. The mechanisms and slip vectors of earthquakes generated by the Katun Fault remain unknown. Its geometry was interpreted as a dextral strike slip (Yin, 2010) or an extension fault (Lukina, 1996; Trifonov et al., 2002). Both interpretations imply a stress setting of quasi-horizontal transtension, which was inferred for the southern fault end from seismological data (Zhalkovskii et al., 1995). The quasi-horizontal and oblique extension axes are directed to the NE and the maximum stress is along the NW horizontal or vertical directions (Goldin and Kuchai, 2007; Rebetsky et al., 2013). According to morphotectonic studies, the backbone fault together with its pinnate faults makes up a zone of extension, 20–40 km (on the northern flank) wide and up to 200 km long (Deev et al., 2012b). There are several graben basins along the fault zone (Deev et al., 2012b, 2015). This paper describes the secondary seismogenic deformations occurring in the Yaloman and Manzherok grabens (Figs. 1b and 2). The Yaloman graben is located in the southern end of the Katun Fault (Fig. 1b). Geomorphically, it is an N–S trending broad segment of the Katun valley, up to 3 km in width and 43 km in length (Fig. 2). About sixty instrumental earthquakes have been recorded within the graben, the largest one (M = 6, 21.04.1927) 10 km southeast of its southern end (Fig. 2). The Manzherok –Graben (Fig. 1b) is the northernmost of several basins in the northern end of the Katun Fault (Deev et al., 2012b). Geomorphically it corresponds to a 35 km long and 3–4 km wide broad segment of the Katun Valley. According to seismological evidence, M = 3.0–5.0 earthquakes are known within the Manzherok -Basin (Fig. 1b). Paleoseismological research in the Yaloman and Manzherok grabens revealed seismites produced by M > 5.0–5.5 Middle Pleistocene – Holocene events (Deev et al., 2005, 2012b, 2015).

2.2. Stratigraphy

The stratigraphy of the study area is given by Efimtsev (1964), Carling et al. (2002, 2009), Lehmkuhl et al. (2006), Zolnikov (2008), Carling (2013), Zolnikov and Deev (2013), Zolnikov et al. (2015, 2016), Deev et al. (2015), and Baryshnikov et al. (2015). The grabens along the Katun Fault are filled with Quaternary deposits, occasionally up to 400 m thick. The alluvium (Q1-2) deposited during the main phase of the Cenozoic orogeny (Fig. 3). The main volume of Quaternary deposits is represented by Middle-Late Pleistocene sediments (the Inya and Saldzhar formations) that were deposited by glacial megafloods (Fig. 3). According to a modified model of Carling (2013), a common vertical stack of sequences in any one succession consists of (1) basal thick coarse parallel-bedded units, (2) large-scale clinoforms, (3) horizontally-bedded thin laminated units, (4) ripple and dune cross-beds, and (5) succession-capping debris flow deposits (in some cases). We are more interested by the horizontally-bedded thin laminated units, that underlie in the sections the SSDS containing deposits or that take part in the deformations alongside them. The units, a few tens of meters thick, are composed of angular granule to fine pebble, gravel, sand, and silt with parallel-planar to slightly wavy horizontal or very low angle bedding (Carling et al., 2002; Zolnikov, 2008; Carling, 2013; Zolnikov et al., 2015). Such bedding may be due to rapid deposition from a deep highly sediment-charged pulsating stream with laminar flow. The cross and inclined bedding indicates that the flow was often of both laminary and turbulent types. Fine deposits may include interlayers of angular and rounded pebbles or occasionally large stone blocks.

The deposits of glacial megafloods coexist with those of lakes formed as they dammed river valleys. Such lake sediments are nearly parallel-bedded silt and sand, up to 1–6 m thick (Carling et al., 2002, 2009; Zolnikov, 2008).

The age of the Inya Formation has been constrained by a single isotope date of 152.0 ± 20.0 ka (RLQG 2207-093) from the Ust’-Chuya section (Fig. 3; Fig. 4; Fig. 5a; Online Supplement 1). Mega-flood events in Gorny Altai formed in two time spans separated by an erosion gap before 80–90 ka BP and ceased after that time (Zolnikov et al., 2016). The Inya and Saldzhar formations lie at the base of high and medium erosion terraces rising, respectively, 350 m and 60 m above the Katun level. Few terraces cut in the Saldzhar Fm. are covered with alluvium, 89 ± 10 ka the oldest (RISO-132543, Yaloman section, Fig. 3; Online Supplement 1). The available IR-OSL and AMS 14C ages of alluvium on lower terraces are 18.9 ± 1.5 ka (RLQG 2205-093), 10.400 ± 50 BP (GRa-59490), or cal BP 12,430–12,060 (2σ), and 10,570 ± 50 BP (GRa-59489), or cal BP 12,670–12,415 (2σ) (Maliny Yaloman section, Fig. 3; Online Supplement 1). Alluvium upon the terrace surfaces coexist with sand and silt deposits of landslide-dammed lakes. The sand and silt samples from the Ust’-Chuya, Katun, and Yaloman sections have IR-OSL and OSL ages of 38 ± 4 ka (RISO-142566), 25.2 ± 1.9 ka (RLQG 2206-093), 19.7 ± 2.3 ka (RLQG 2184-053), and 18.6 ± 1.4 ka (RLQG 2210-093) (Fig. 3; Online Supplement 1).

The terraces, with sediments on their surfaces, are overlain by subaerial facies of Late Pleistocene-Holocene loess, aeolian sands, colluvial aprons, and alluvial fans. Aeolian sands from the Katun section have an IR-OSL age of 7.7 ± 0.6 ka (RLQG 2211-093) (Fig. 3; Online Supplement 1), while talus samples show OSL, TL, and IR-OSL ages from 25.7 ± 50 BP (GrA-59489), or cal BP 1.9 ka (RLQG 2202-093), 1.4 ka (RLQG 2195-093), and 1.2 ka (RLQG 2201-093) (Fig. 3; Online Supplement 1). The alluvium of low terraces and floodplains accretes to the Katun streambed.

Many SSDS form by liquefaction and fluidization of wet soft sediments, especially silt and sand (Tsuda and Hayashi, 1971; Sibiryakov and Deev, 2008) exposed to coseismic shaking. It is thus reasonable to look for seismites in fine-grained lacustrine deposits (Rodríguez-Pascua et al., 2000; Üner, 2014; Gladkov et al., 2016). Therefore, the sections containing limnic facies and overbank alluvium were examined with special care.
Fig. 3. Simplified stratigraphy of sediments that fill the valley of the Katun River and its side tributaries. Not to scale.

Fig. 4. Ust'-Chuya section, modified after (Deev et al., 2009).
3. Material and methods

3.1. Active faults and paleoseismological studies

Faults were detected using Landsat and QuickBird satellite images (http://earth.google.com), shaded relief maps (GeoMapApp 3.4.1., http://www.geomapapp.org), sheets of the 1:25,000 to 1:200,000 scale topographic map compiled by the Federal Service of Geodesy and Cartography (Russia), sheets of the 1:200 000 scale State geological map of the Russian Federation, and published maps of active faults in Gorny Altai (Lukina, 1996; Trifonov et al., 2002). Motions on faults are recorded in displacement of Cretaceous–Palaeogene preorogenic erosion surfaces, deformation of Neogene and Quaternary deposits, as well as in offset river valleys, lake terraces, alluvial fans, etc. The locations of historical and instrumental earthquakes were borrowed from the IRIS seismic catalog, from the catalog of Ulomov and Medvedeva (2011), and from 1963 to 2009 data of the Altai–Sayan Department of the Geophysical Service of the Russian Academy of Sciences.

SSDS were attributed to seismic causes proceeding from published criteria (Sims, 1975; Hempton and Dewey, 1983; Anand and Jain, 1987; Owen et al., 2011; Owen and Moretti, 2011; Moretti and Van Loon, 2014; Deev et al., 2009, 2013, 2015). Earthquake-induced deformation structures were typified according to existing classifications (Hempton and Dewey, 1983; Plaziat et al., 1990; McCalpin, 1996; Rodríguez-Pascua et al., 2000; Owen, 2003; Montenat et al., 2007).

Out of all identified SSDS only measurements of the dimensions (width and height) of silt and sand dikes were used for estimation of the $M_S$ magnitude and shaking intensity for just one paleoearthquake, using the empirical relationships of Lunina and Gladkov (2015). Magnitudes of other paleoearthquakes were estimated using data synthesis from different regions worldwide (Kuribayashi and Tatsuoka, 1975; Ambraseys, 1988; Galli, 2000;
Papathanassiou et al., 2005). Estimations of shaking intensities were done using the ESI 2007 scale.

3.2. Sedimentological studies of Late Quaternary sediments sections

Sedimentological studies were performed in outcrops mapped on a 1 × 1 m grid or in quarry sections correlated with one another using panoramic photographs. The sections were documented in terms of color, angle and thickness of bedding, grain sizes, deformation patterns, gravel orientations, and sediment genesis. Grain sizes in some selected samples were determined by sieving.

3.3. Human burial documentation

Archaeological studies of burial mounds at the Chultukov Log 1 site included search for vegetated burials with stone mounds (cairns) above them, which lost clear geomorphic expression because of the wet climate in the Northern Altai. Continuous excavations were applied to constrain the relative positions of individual burials. The cairns were freed from vegetation and then cleaned further by scoops, brushes, and knives. During the excavations, main elements of burials were identified as an outer wall and an original circular outer boundary. Stone rings were identified from their larger blocks, circular position on the mound periphery, fitting to one another, and relation with the stone mounds. After clearing, identification, and imaging (in field sketches and photographs), the stone mounds were dismantled to find the base stone circles. Each step of the dismantling procedure was documented (sketched and photographed): (1) intact mound; (2) main stone mound; (3) stone circle and chamber (grave pit) in the center; (4) dug mound, cleared stone circle, and a stone box with bones.

3.4. Chronology

IR-OSL ages of lacustrine, alluvial, and aeolian sands were obtained at the Research Laboratory for Quaternary Geochronology, Department of Geology, Tallinn University of Technology, Estonia (Dr. A. Molodkov) (Online Supplement 1, Table S1). OSL dating of lacustrine and alluvial sands (2 samples, Table S2) was performed at the Nordic Laboratory for Luminescence Dating, Institute for Geoscience at Aarhus University, Denmark. The AMS 14C ages of humans from dug burials (7 samples, Table S3) and animal bones (2 samples, Table S3) were determined at the Laboratory of Absolute Dating, Krakow, Poland (Prof. M.Krapiec) and at the Center for Isotope Research, University of Groningen, Netherlands (Dr. J. van der Plicht). Calibrated ages were calculated using the OxCal 4.2.3 software (Bronk Ramsey, 2013) and the IntCal2013 calibration curve (Reimer et al., 2013).

4. Paleoseismological study in the Yaloman -Grablen

4.1. SSDS in Late Quaternary sediments

4.1.1. The Ust'-Chuya section

The Ust'-Chuya section is located on the right side of the Katun River, 600 m downstream of its confluence with the Chuya River (Fig. 2). The section (Fig. 4) begins with more than 7 m thick inclined parallel bedded gray cobble, boulder, and pebble megaflood deposits of the Inya Fm. (Unit 1) which enclose 61.5 m of gray lacustrine gravel to fine pebble, outsize sand, and silt (Unit 2); A sand sample from the base of Unit 2 has an IR-OSL age of 152.0 ± 20.0 ka (RLQG 2207-093). Units 1 and 2 are discordantly overlain by megaflood deposits of the Saldzhar Fm. (Unit 3) comprising two beds of nearly horizontal and cross-bedded gray pebble-cobble sized gravel (5 and 9 m thick, respectively), as well as two beds of angular granule and fine pebble, rounded pebble, sand and silt with parallel-planar or very low angle bedding, of the respective thicknesses 4.8 and 3.8 m. Unit 4 consists of gray parallel-bedded silt and sand of a landslide-dammed lake (6.4 m thick) is truncated by 6.8 m thick Unit 5 of gray slope-wash deposits with low-angle cross bedding. A sand sample from the base of Unit 4 has an IR-OSL age of 25.2 ± 1.9 ka (RLQG 2206-093) and two sand samples from the top of Unit 5 have OSL ages of 12.2-6 ± 0.61 ka and 12.91 ± 0.73 ka (Baryshnikov et al., 2015).

We carefully studied the lacustrine deposits of Units 2 and 4 in search for SSDS potentially produced by paleoearthquakes and found eight deformed beds in Unit 2 (B1–B8) and eleven such beds in Unit 4 (B1–B11). The deformed beds of Unit 2 (Fig. 5a; Online Supplement 2), with flame (Fig. 5b–e, g) and ball-and-pillow (Fig. 5f) structures and load casts (Fig. 5b), are from 2.5 to 40 cm thick and fall within the depth interval 1.2 m–4.4 m above the unit base. Most of deformed beds alternate with undeformed sediments of similar grain sizes. The top surfaces of the deformed beds are angular unconformities. Unit 2 is dislocated by normal faults with displacement up to several centimeters, which formed due to contemporary gravitational destruction of the outcrop (Fig. 5b). Judging by the IR-OSL age of a sand sample from B1, the SSDS occurred about 150 ka BP (MIS 6).

The deformed beds of Unit 4 (Fig. 6a; Online Supplement 2) lie 0.45–3.3 m above the unit base, are from 1.5 to 145 cm thick, all separated by undeformed sediments of similar grains sizes. Deformation produced flame (Fig. 6b–e, f, i), and ball-and-pillow (Fig. 6k) structures, load casts (Fig. 6f, g, i), and sand diapirs (Fig. 6d), silt breccias (Fig. 6j), microfaults (Fig. 6e), flexures, and folds. The upper deformed beds (B9–B11) are as thick as 65–145 cm. The deformed beds of this unit likewise have angular unconformities on the top. IR-OSL dating of sand sampled 30 cm above the unit base (B1) suggests multiple deformation events about 25 ka BP (MIS 2). The upper age bound of SSDS corresponds to the 13 ka age of slope-wash deposits on the top of Unit 5.

4.1.2. The Yaloman section

The Yaloman section (Fig. 2; Fig. 7a) is located in the right side of the Malyi Yaloman River (left tributary of the Katun), 900 m southeast of its mouth (50.497614° N, 86.590988° E), in a 120 m long and 15 m deep quarry on a medium terrace, 760 m a.s.l., near the riser base. A stratotype section of post-Saldzhar alluvium was studied in the southeastern wall of the quarry (Zolnikov, 2008; Zolnikov et al., 2015). Alluvium consists of cobble, pebble, and coarse-grained sands with trough cross bedding (Fig. 7b). The troughs are 2–4 m deep, and some are capped by 20–30 cm to 1 m thick parallel-bedded sands. SSDS in one sand-gravel trough sandwiched between undeformed sediments of similar lithology and grain sizes appears as systems of rootless fractures and small micro-faults with <20 cm slip (Fig. 7c–e), flexures, and convolute lamination (Fig. 7f and g). The slip geometry (lack of normal faults, dipping towards the slope direction) indicates motions that had no relation with possible gravitational sliding of sedimentary material. This is also confirmed by the location of troughs with SSDS in stratigraphic sandwich between undeformed sediments (Fig. 7a–e, g). SSDS was timed according to the 89 ± 10 ka OSL age of a sand sample (RISO-132543) from a depth of 13.2 m (Zolnikov et al., 2016).

4.1.3. The Katun section

The Katun section (Fig. 2) is located on the left side of the Katun River, 1 km southwest of Malyi Yaloman Village, at 50.50570° N, 86.56667° E. The terrace section, 580 m long and 30 m high above the water level, comprises four units (Fig. 8a). Unit 1, 24 m base of the medium terrace, 720 m a.s.l., consists of megaflood cross-bedded (~30°) gravels. The megaflood deposits are overlain by
alluvial gravels and sands with trough cross bedding up to 8 m thick (Unit 2). Unit 3 is composed of 12 m thick parallel-bedded sand and silt deposited in a landslide damlake which fills the Katun River paleo-channel (30 m deep and 300 m wide). The lacustrine deposits of Unit 3 documented in detail comprise ten 0.5–10.5 cm thick deformed beds in the middle, from 5 to 8 m above the base (Fig. 8a and b; Fig. 10; Online Supplement 2). SSDS caused mixing of sediments with different grain sizes and produced flame (Fig. 8c, e) and ball-and-pillow (Fig. 9c) structures, load casts (Fig. 8c, e; Fig. 9f), pseudonodules (Fig. 8e; Fig. 9g and h), diapirs (Fig. 9d), folds (Fig. 8e; Fig. 9a and b), and convolute lamination (Fig. 8d and e; Fig. 9e). Some deformed beds are separated by undeformed sediments of similar grain sizes and angular unconformities. The age of SSDS was estimated by IR-OSL dating of lake sand samples. One (RIS0-142566) sampled 1.5 m below bed B1 (Fig. 8a) has an OSL age of 38 ± 4 ka (Zolnikov et al., 2016), which falls within MIS 3, and another one from the top of Unit 3 has an IR-OSL age of 18.6 ± 1.4 ka (RLQG 2210-093). The section is capped by 2.5 m of aeolian sand (Unit 4). A sand sample from its base has an IR-OSL age of 7.7 ± 0.6 ka (RLQG 2211-093).

4.1.4. The Malyi Yaloman section

The Malyi Yaloman section (Fig. 2; Fig. 10a) is located on the left side of the Malyi Yaloman River 3.5 km upstream of its mouth.
Figure 7: Yaloman section (a), modified after (Zolnikov et al., 2015); b: trough cross-bedded alluvial gravel; c–g: SSDS in alluvial gravel and sand, modified after (Deev et al., 2009, 2015): cracks and micro-faults (c–e), flexures (f), convolute lamination (g). GPS receiver and pen are for scale.

(50.48192° N, 86.57664° E) and consists of six units (Fig. 10b). Unit 1 at the base, 3.5 m of visible thickness, is composed of parallel-planar bedded gray angular granule and fine pebble deposited by megafloods (Saldzhark Fm.), with layers of outsize sand, silt, angular pebble and cobble. Unit 2 is composed of yellowish-gray deposits of a landslide-dammed lake, up to 1.5 m thick: parallel-planar horizontal bedded silt and medium to fine sand in the lower and upper thirds, separated by fine pebble, granule, coarse to fine sand, and silt. The IR-OSL age of a sand sample (RLQG 2184-053) from the Unit 2 middle is 19.7 ± 2.3 ka. Unit 2 is partly deformed and split by a 1.3 m thick and 8 m long lens of gray massive angular gravel in a sand and silt matrix deposited by a mudflow (Unit 3). The mudflow caused slightly wavy bedding in the upper part of Unit 2. Alluvial Units 4 and 5, 0.5 m and 1.5 m thick, respectively, are composed of gray trough cross-bedded pebble, cobble, and boulder deposits with sand layers. The IR-OSL age of a sand sample (RLQG 2205-093) from the middle of Unit 4 is 18.9 ± 1.5 ka. The top of Unit 5 contains bone fragments of *Cervus elaphus* (a tibia fragment, 10 cm below the top) and *Capra sibirica* (a jaw, 40 cm below the top), with AMS 14C ages of 10,400 ± 50 BP (GrA-59490), or cal BP 12,430–12,060 (2σ), and 10,570 ± 50 BP (GrA-59489), or cal BP 12,670–12,415 (2σ), respectively. The section is capped by redeposited material of high and medium terraces (>13 m thick): yellowish-gray colluvial (slope-wash) angular pebble, sand, and silt with parallel-planar horizontal and low-angle bedding, angular truncations, and small paleochannels.

SSDS appear at four levels. The first three events occurred at about 20 ka BP, during deposition of Unit 2. The top of silt and sand in the lower third of Unit 2 contains discordant surfaces and pillar structures produced by plastic deformation and rupture of thin silt layers by liquefied sand. The deformation is responsible for the angular unconformity between the lower and middle parts of Unit 2 and for the presence of fine pebble, granule and coarse sand in its middle part.
Sand in the upper third of Unit 2 includes a 10 cm thick deformed bed with folds of 13–15 cm wavelengths which result from mixing of liquefied medium-grained sand lying above fine and very fine sand. The deformed bed is traceable for a distance of 10–15 m and is sandwiched between undeformed lacustrine deposits. Finally, the lacustrine deposits of Unit 2 were partly deformed and split by a mudflow (Unit 3) during outburst of the landslide-dammed lake, and thus became exposed to subaerial conditions, which led to thin platy jointing in silt on the top.

The deposits of Units 1–4 were bent at a low angle over a distance of 100 m, faulted and fractured during the fourth event (Fig. 10b); the amount of normal and reverse slip reached 0.5 m. The deformation features decay gradually downstream the Malyi Yaloman and are truncated by alluvium of Unit 5. The time of deformation is bracketed between 19 and 12.5 ka BP according to the AMS $^{14}C$ and IR-OSL ages of samples from Units 4 and 5. The deformation event is marked by an angular unconformity at the base of Unit 5.
4.1.5. The Malyi Yaloman section-2

The Malyi Yaloman section-2 is located in a 5 m terrace on the left side of the Malyi Yaloman 300 m downstream of the Malyi Yaloman section, at 50.48364° N, 86.58014° E (Fig. 2), and comprises seven units (Fig. 11a). Unit 1 (megaflod deposits of the Saldzhar Fm.), more than 1.9 m of visible thickness, is a stratigraphic and lithological equivalent of Unit 1 from the Malyi Yaloman section. Unit 2 is composed of alluvial gray trough cross-bedded pebble, cobble, and boulder deposits intercalated with sand and is a stratigraphic equivalent of Unit 5 in the Malyi Yaloman section. It has rough top and base surfaces and a variable thickness of 0.3–2.5 m. White, gray, and yellowish-gray silt and outsize sand of Unit 3 (0.2–1.5 m thick) is overbank alluvium, likewise with very rough top and base surfaces. Unit 4 composed of yellowish-gray slope-wash angular pebble, sand, and silt is a stratigraphic equivalent of Unit 6 from the Malyi Yaloman section. The section completes with Unit 5 (up to 1.1 m thick) of gray alluvial cobble and pebble in a sand matrix, Unit 6 (0.4 m thick) of pale yellow and whitish slope-wash silt and gravelly sand, and Unit 7 of modern soil (0.2 m).

Liquefaction-like SSDS appear at the top of Unit 1, where coarse gravel of Unit 2 sinks into underlying material (Fig. 11b). The deposits of Units 1–4 (Fig. 11a) were jointly involved in larger-scale SSDS: mixed to produce 2–3 m structures of interfingering liquefied material of different grain sizes (Fig. 11c). Deformation is responsible for large sediment thickness variations. In some cases, alluvial gravel of Unit 2 penetrates through whole Units 3 and 4 (Fig. 11d). The deposits of Unit 4 are cut with dikes (to 0.9 m thick.

Fig. 9. SSDS of deformed bed 9. a: disharmonic folds; b: symmetrical folds; c: ball-and-pillow structures; d: sand diapirs injected into overlying silt; e: convolute lamination; f: load casts; g-h: pseudonodules.
and 2.5 m high) resulting from fluidization of silt and sand of Unit 3 (Fig. 11e). Units 1–4 are also heavily deformed by steep and vertical fractures and faults with small amounts of displacement (a few cm to a few tens of cm). The deformation structures are sealed and truncated by alluvial gravel of Unit 5 (Fig. 11a). The lower age bound of SSDS is constrained by the 12.5 ka AMS14C age of samples from the Malyi Yaloman section.

4.1.6. The Malyi Yaloman section-3

The Malyi Yaloman section-3 (Fig. 2) is located in a small gully that strips the next terrace located in 100 m to the west (50.48359° N, 86.57871° E). The SSDS are restricted to slope-wash deposits of Unit 1 (Fig. 12a), which is a stratigraphic and lithological equivalent of Unit 4 in the section Malyi Yaloman-2 and Unit 6 from the Malyi Yaloman section. They are mainly fractures and micro-faults with amounts of slip reaching 20 cm in yellowish gray parallel-planar and lenticular bedded angular very fine to fine pebble and sand (Fig. 12a and b). In some cases, slope-wash deposits are turned around thus producing slopeward dips of the bedding planes. The section contains silt and sand dikes, from 2 to 3 to 30 cm thick (Fig. 12c). The SSDS are truncated by 1.0–1.5 m of grayish-yellow trough cross-bedded alluvial gravel with a sand matrix (Unit 2). The section is capped by silty sand with enclosed pebbles up to 1 m thick (Unit 3), and a 10–20 cm thick modern soil (Unit 4). Thus, the style and stratigraphic position of the deformation event correlate with that of <12.5 ka BP in the Malyi Yaloman section-2.

4.1.7. The Malaya Inya section

Two deformed beds in a stratigraphic sequence similar to the Malyi Yaloman section and the Malyi Yaloman section-2 were
discovered in the Malaya Inya Valley, the right tributary of the Katun River, 7.7 km farther southeast. Stratigraphic sequence similarity of three sections is determined by the analogous sequence of sedimentation events in the neighbouring inflows of Katun R.: sedimentation in a landslide-dammed lake — alluvial channels and sedimentation — accumulation of slope-wash deposits. The Malaya Inya section is located in the right side of the Malaya Inya River, 3 km upstream of its mouth (Fig. 2), and includes five units (Fig. 13a and b). Unit 1 is composed of lacustrine gray silt and very fine to medium sand, at least 0.6 m thick. It is a stratigraphic equivalent of Unit 2 in the Malaya Inya section. Unit 2 consists of 0.4 m thick alluvial very low angle cross-bedded sand, angular granule and fine pebble, and is a stratigraphic equivalent of Unit 4 from the Malaya Yaloman section. Units 1 and 2 contain flame structures produced by sediment mixing and load casts (Fig. 13a, c). The SSDS are truncated by 3.2 m thick gray trough cross-bedded alluvial deposits of Unit 3. The sediment grain sizes vary from granule and fine pebble in the lower part of Unit 3 to pebble-cobble gravel in its upper part, which is locally yellow-brown (Fig. 13a and b). Unit 3 is a stratigraphic equivalent of Unit 5 in the Malaya Yaloman section and Unit 2 in the Malaya Yaloman section—2. Unit 4 is composed of plane-bedded alluvial yellowish gray silt and sand with 0.9 m thick low-humus layers; it is equivalent to Unit 4 from the Malaya Yaloman section—2. Unit 5 at the section top consists of slope-wash yellowish gray angular granule and fine pebble (2 m thick) and is equivalent to similar slope-wash deposits in the three Malaya Yaloman sections. Sediments of upper Unit 3 form gravel diapirs that intrude and deform Unit 4 and lower Unit 5 (Fig. 13b, d).

4.2. Seismic trigger criteria for SSDS

The SSDS we have revealed are of seismogenic origin. The seismic trigger can be inferred using published criteria (Sims, 1975; Hempton and Dewey, 1983; Anand and Jain, 1987; Moretti and Van Loon, 2014). The list of these criteria was complemented with reference to our data and applied to deformation in the Late Pleistocene-Holocene Yaloman sediments. Namely, the deformation structures in the study area.

(1) Occur in sections located in the zone of active Quaternary mountain growth and within the zone of the active Katun Fault, which generated M ≤ 6 instrumental and historic earthquakes;

(2) Neither from SSDS to those identified in Quaternary deposits sections of the Yaloman Graben can be related to subaerial or subaquatic gravity sliding, judging by the absence of geomorphically expressed signatures of landslides in the immediate vicinity of the sections. The sampled sections contain neither bedding slip signatures nor systems of reverse and thrust faults and folds aligned with slope direction which commonly mark landsliding (Alsop and Marco, 2013; Gladkov et al., 2016; Zolnikov et al., 2017). We emphasize especially that the geometry of micro-faults in the Yaloman section corresponds to slip opposite the gravity slope direction (Fig. 7c, e).

Morphologically similar SSDS can form due to glaciogenic features and cryoturbation (Patton and Hambrey, 2009; Alexeev et al., 2014; Gruszka et al., 2016). Glaciogenic features can be easily discarded since the studied sections are located in the periglacial zone. Cryoturbation is a subaerial process and does not occur in lacustrine settings. The upper level SSDS in the Malaya Inya section (Fig. 13a–b, d) are the closest to cryoturbations morphologically and by the subaerial setting of their formation. However, in our
case, the SSDS are a single event, while the cryoturbation process usually involves repeated mixing of sediments, with inclusion of layers and humous interbeds. In addition, the most widespread form of cryogenic deformations are cryogenic wedges, but these have not been identified in the Yaloman Graben sections.

Sand dikes can form due to change in the water-table level during floods in lowlands along rivers (Obermeier et al., 1990). However, the association of sand dikes we identified in the Malyi Yaloman-2 section with multiple faults with slip amounts within a few tens of cm and gravel diapirs up to 2—3 m high, leaves no doubt that the formation of these structures was seismogenically triggered. The strike of the dikes also indicates that they are subparallel to the normal faults bordering the Yaloman Graben.

The most debated is the nature of the load structures (ball-and-pillow structures, load casts, pseudonodules, and partially flame structures and convolute lamination). They can form without shaking due to gravity-induced instability of denser sediment overlying less dense sediment. The following settings are favorable to this: (1) the formation of channelized erosional surfaces can induce unequal loading effects; (2) the unequal loading of migrating ripples of sand or silt; (3) high instantaneous sedimentation rates (overloading) (Lowe, 1975; Obermeier et al., 1990; Dasgupta, 1998; Moretti and Sabato, 2007; Moretti and Ronchi, 2011). The first two triggers are excluded since no channelized erosional surfaces and ripple cross-laminations were discovered in the lacustrine deposits of the Ust’-Chuya and Katun sections. Load structures, formed during unequal loading of migrating ripple cross-laminations could have been expected between Unit 1 and 2 of the Malaya Inya section (Fug. 13c). But in that case the SSDS would have a completely different morphology, and show progressively deformed radial internal lamination caused by the rotation of the ripple cross-laminations as the ripples sink.

Fig. 12. a: Malyi Yaloman-3 section; b, c: faults (b) and sand dikes (c) in deposits of Unit 1.
Rapid sedimentation is a very common trigger mechanism for liquefaction in sand-on-sand systems and sand-in-clay systems (Moretti et al., 2001). This trigger can be excluded for the SSDS of Unit 3 of the Katun section (Fig. 8; Fig. 9) and of Unit 4 (Fig. 6) of the Ust’-Chuya section for the following reasons: (1) thin horizontally-laminated parallel-bedded sand and silt accumulated in a setting that precluded rapid sedimentation; (2) the SSDS often include sequences of several sand and silt layers (Fig. 6c and d; Fig. 8d and e; Fig. 9a–b, f); (3) SSDS within one deformed bed are represented by different structures, including ones not corresponding to load structures (Fig. 6c and d, Fig. 9a–b, d). SSDS in the lower part of Unit 2 of the Ust’-Chuya section (beds B1-B6) could have formed as a result of overloading (Fig. 5a-e). However, their concentration in a narrow interval and the lack of layers in granulometrically similar pairs (granule and coarse sand overlapping medium sand) above and below this interval (Fig. 5a and b), in our opinion, indicates a seismogenic trigger. Furthermore, all three triggers responsible for the formation of load structures are most typical for settings where sands and silts overlap muddy or extremely soft clay (Dzulynski and Walton, 1965; Obermeier et al., 1990; Moretti and Ronchi, 2011). In our case, muddy sediments are not present in the observed deformed beds.

As morphological analogs of the SSDS that can form by wave-induced liquefaction (Molina et al., 1998; Alfaro et al., 2002), only folds the sands of the upper third of Unit 2 of the Mal’ya Yaloman section can be considered. However, the following observations indicate that wave-induced liquefaction cannot be accepted as a trigger for the formation of these SSDS. According to Alfaro et al. (2002), a minimum 6 m of wave height can produce liquefaction. While during the formation of Unit 2, waters of a landslide-dammed lake flooded the valley of the Mal’ya Yaloman River — a left-bank lateral inflow of Katun River. It is improbable that strong storms with the potential of liquefying sediments could take place in such a narrow and shallowly flooded valley.

(3) Correlate in scale and morphology with those produced by liquefaction and fluidization of sediments during instrumental and historic earthquakes, with fossil seismites from other seismic areas (Hempton and Dewey, 1983; Plaziat et al., 1990; Rodríguez-Pascua et al., 2000; Joshi et al., 2009; Moretti and Ronchi, 2011; Üner, 2014), as well as with structures in saturated sediments formed experimentally in shaking tests (Kuenen, 1958; Owen, 1996; Moretti et al., 1999);

(4) are stratigraphically sandwiched between undeformed sediments of similar grain sizes which discordantly overlie or truncate the tops of the deformed beds. This is evidence of discrete and recurrent deformation events common to active seismic areas where spells of activity alternate with quiescence;

(5) have broad lateral extent: two structures from the same stratigraphic level spaced at 7.7 km correlate in two cases (the Mal’ya Yaloman and Mal’ya Yaloman-2 sections, and the Malaya Inya section), and multiple deformed beds in deposits of dam lakes are traceable for 14 km (the Mal’ya Yaloman, Katun, and Ust’-Chuya sections).

Thus, the SSDS we observed have had seismic triggers and belong to seismites (Seilacher, 1969). Seismites are diverse deformation structures that result from earthquake-induced brittle deformation and liquefaction or fluidization of soft sediments with different moisture contents. Seismites in sedimentary sequences appear as silt-sand dikes or diapirs; systems of fractures and faults;
mixture of layers with different grain sizes; folds, etc. (Seilacher, 1969; Hempton and Dewey, 1983; Plaziat et al., 1990; Rodríguez-Pascua et al., 2000; Montenat et al., 2007; Deev et al., 2009, 2013, 2015). They are reliable paleoseismological guides as (i) they are far more frequent and better preserved in active regions than primary deformation structures, which become fully eroded in thousands or tens of thousand years, and (ii) being sealed in sediments, they can hold through Late Pleistocene and Holocene and even as long as tens or hundreds of million years (Rossetti, 1999; Netoff, 2002; Jewell and Ettensohn, 2004; Mazumder et al., 2006).

5. Archaeoseismological studies in the Manzherok Graben

5.1. The burials at the Chultukov Log 1 site

The possibility of using archaeoseismic damage to burial mounds, typical archaeological objects in Central Asia, as a guide to parameters of prehistoric and historic earthquakes was demonstrated by Trifonov et al. (1988) and Deev et al. (2012b, 2016, 2017). The burials at the Chultukov Log 1 site are located in the northern end of the Katun Fault (Fig. 1b), 2 km northwest of Manzherok Village, on the surface of a 6 m high terrace of the Katun River next to a bedrock rise (Fig. 14a). The riser base is buried under talus which, along with the Katun alluvial gravel, was used for building the stone mounds. Currently 123 intact mounds, 2–15 m in diameter and 0.1–0.5 m high, have been detected within the necropolis. They belong to the Bystrynanka, North Pazyryk, and Kara-Koba cultures of the Gorny Altai early Iron Age, Scythian time, or to the Maima culture of the Hun-Sarmatian time (Borodovskiy and Borodovskaya, 2013).

Seven burials (Nos. 3, 4, 13, 53, 54, 55, and 74 in Fig. 14b) of the Bystrynanka culture (6th to 2nd centuries BC), except for No. 13, are located in the southeastern periphery of the necropolis. Each burial includes a cairn made of outsized colluvium, a stone ring below it, and a chamber with a stone box in the center, with stone plates or large stones, and/or wooden frames, along its inner walls, to a half-height (0.6–0.7 m), and cover plates on the box top. All bodies are in the supine position, with the head to the north or northwest (Borodovskiy and Borodovskaya, 2013).

Most of burials at the Chultukov Log 1 site are of North Pazyryk type (6th through 3rd centuries BC), with bodies folded and lying on the right side and with the head to southeast. At the head, there are Pazyryk-type ceramic pots decorated with carved ornaments and red-and-black paint. The cairns are built mainly of colluvium in male burials and of the Katun alluvium pebbles and cobbles in female ones. The stone rings consist of larger blocks, often laid in several rows. The North Pazyryk burials at the Chultukov Log 1 site typically contain wooden frames, instead of or together with large flat stones along the chamber inner walls. The frames apparently supported a wooden cover on the chamber top. Some chambers are also floored by wood (Borodovskiy and Borodovskaya, 2013).

Twenty two burials (Nos. 6, 7, 8, 9, 25, 37, 44, 45, 50, 58, 64, 79, 88, 100, 110, 111, 112, 114, 115, 116, 118, and 122 in Fig. 14b) of the Kara-Koba culture (5th through 3rd century BC, Fig. 15a and b) were found in the central and northeastern parts of the necropolis. They differ in the presence of boxes made of stone plates with a cover on top (Fig. 15c and d). The dead bodies are folded, lying on their right side, with the arms along the sides and the head to east-, southeast- or southwestward. The cairns of Kara-Koba burials consist of stones larger than 25 cm and lie upon a stone ring around a stone box. The chamber walls are lined with upright stone plates. The boxes are covered by a stack of several stone plates (Borodovskiy and Borodovskaya, 2013).

Nine burials (Nos. 59, 60, 61, 62, 63, 67, 70, 73, and 86) that belong to the Maima culture of the Hun-Sarmatian time (1st to 5th centuries AD) were found in the southeastern end of the necropolis (Fig. 14b). The cairns, at least 2 m in diameter, made of colluvium, have no prominent geomorphic expression. The stones are generally smaller than those over the early Iron Age burials. The mounds are closely spaced and often merge with one another. Under the cairns, there are elliptically arranged large stones in all mounds. The dead bodies lie in ground pits, 1.7 m long, <0.7 m wide, and 0.19–0.5 m deep, in the supine position, at arbitrary orientations, with the arms slightly folded at the elbow. Most of burials lack wooden or stone inner walls. Shallow pits of the Maima culture were filled with earth.

5.2. Deformations of the burial mounds

The mounds over early Iron Age burials located at the foot of the bedrock slope are made of colluvium. There are 1.5–2 m stones randomly scattered as far as 25 m away from the slope, not far from the group of burials; some stones lie upon early Iron Age burials and deform the cairns and the stone rings (Fig. 15a and b; Fig. 16a-d). Stones or plates used for chamber inner walls or cover are displaced. In some cases, stones and plates are fallen down inside the chamber and distort the anatomic order of bones (Fig. 17a-d). On the other hand, there is no direct correlation between the presence of colluvium blocks over the mounds and deformation of the burial interior. Some mounds where the cairns and stone rings are deformed have intact chambers (Fig. 15c and d), but the anatomical order of bones is distorted in other burials located 50 m far from the bedrock slope outside the colluvium. Note that no deformation has been observed in the Maima burials (1 millennium AD), though the mounds lie upon talus or upon large bedrock fragments.

5.3. Comparison criteria for the deformations of the Chultukov Log 1 burial mounds with the paleoearthquake

The damage observed in burial mounds of the Chultukov Log 1 site can be related to seismic events on the basis of several criteria.

1. The group of burial mounds at the Chultukov Log 1 site is located in the southern Manzherok Basin which formed in the Quaternary within the zone of the active Katun Fault. Currently faults within the basin generate M < 5.0 events, but traces of M > 5.0–5.5 Late Pleistocene earthquakes in the Saldzhak deposits were found 43.3 km southeast of the necropolis (Deev et al., 2012b).

2. The burials bear signatures of damage to their both exterior and interior elements. The interior elements are deformed: directed collapse of stone box walls and rotation and crushing of stones. Similar coseismic deformation was reported from stone archaeological objects of various types (Korjennyk and Mazor, 1999; Rodríguez-Pascua et al., 2011). Importantly, damage of chamber interior was observed also in the cases of no exterior damage.

3. The chamber interior was damaged in burials of different cultures of the early Iron Age, i.e., deformation can hardly result from specific construction defects.

4. The interior damage cannot be caused by people as the graves have never been looted.

5. Deformation cannot result from landsliding, as no respective geomorphic signatures have been found in the surroundings of the necropolis. The lack of damage to the walls of ground pits (Fig. 16d; Fig. 17a-d), as well as in pit wall sections, rules out lateral spread, soil creep, or similar processes as causes of failure in the stone boxes.

6. The burial mounds were created with an obvious time gap: most of the necropolis with deformed mounds appeared between the
5th and 2nd centuries BC while nine mounds on the southern margin date back to the earliest 1st millennium AD and lack signatures of damage.

6. Discussion

6.1. The age of paleoearthquakes

Investigation into seismites has important implications for extending the earthquake record back into the past. In this context, and as applied to our work, the sedimentary sequences containing seismites can constrain the number and ages of paleoearthquakes. Our studies revealed single and multiple past events with ages of ~150 and 90 ka, in the 38–19 and 19–12.5 ka intervals, and younger than 12.5 ka (Table 1). The events recorded in the Katun section with ten deformed beds in an interval of 20 ka, recurred approximately every 2000 years (Fig. 8a).

The event that may be responsible for the archaeoseismic damage at the Chultukov Log 1 site can be timed according to the ages of cultures identified within the necropolis, supported by AMS 14C dating of bones. The bones of the dead have the following ages (Borodovsky et al., 2015): 2560 ± 80 BP or 840 ± 410 cal BC (2σ) for No. 109 (MKL-1916); 2550 ± 90 BP or 845 ± 405 cal BC (2σ) for No. 115 (MKL-2525); 2280 ± 70 BP or 545–160 cal BC (2σ) for No. 111 (MKL-2524); 2190 ± 80 BP or 400–50 cal BC (2σ) for No. 114 (MKL-2526); 2160 ± 70 BP or 385–45 cal BC (2σ) for No. 123 (MKL-2522); and 2065 ± 80 BP or 260 cal BC–85 cal AD (2σ) for No. 118 (MKL-2527). Thus, the earthquake may have occurred in the interval between the 3rd century BC and the 1st century AD.

6.2. Using seismites and the damage to burial mounds to estimate earthquakes parameters

Seismites hardly can exactly point to locations and magnitudes of ancient earthquakes (Obermeier, 1996; Kremer et al., 2017) for several reasons: diverse SSDS can result from earthquakes of different magnitudes and can occur within a large range of distances from epicenters (Ambraseys, 1988; Galli, 2000; Papathanassiou et al., 2005); they are often hidden under younger sediments or vegetation; reliably correlated sections with seismites are few. Meanwhile, data synthesis from different regions worldwide shows that liquefaction and fluidization of shallow soft wet sediments are common consequences of M ≥ 5–5.5 earthquakes (Kuribayashi and Tatsuoka, 1975; Ambraseys, 1988; Galli, 2000; Papathanassiou et al., 2005), i.e., they arise at shaking intensity I ≥ VI–VII on the ESI 2007 intensity scale. Instrumental earthquakes originated at depths from 10 to 40 km in the mountains of southern Siberia, Mongolia, and northeastern Kazakhstan can cause liquefaction and fluidization when their magnitudes reach Mw = 5.2 or higher (Andreev and Lunina, 2013).

In the case of instrumental earthquakes in southern Siberia (1950–2008), structures of liquefaction and fluidization appear most often within 40 km (93%) or 20 km (70%) from the respective

![Fig. 14. a: necropolis at Chultukov Log 1 site, general view; b: sketch map of Chultukov Log 1, modified after (Borodovsky and Borodovskaya, 2013).](image-url)
seismogenic faults (Lunina et al., 2014). The liquefaction and fluidization effects caused by the 27.09.2003 Chuya earthquake were observed within 50–55 km from the epicenter (Rogozhin et al., 2007), which fits this range. Therefore, the ancient earthquakes responsible for various secondary soft-sediment deformation structures we revealed may have been generated by the Katun Fault.

Large-scale structures of sediment mixing that involve alluvial pebbles and dikes, in the sections of Malyi Yaloman—2 and 3 and Malyaya Inya can place constraints on the location of one such event. Liquefaction structures in gravel to pebble-sized sediments are known to be associated with M/C21e8 earthquakes (Rodríguez-Pascua et al., 2000; Bezerra et al., 2005). Judging by the height and width of sand dikes, the magnitude of the Holocene event younger than 12.5 ka can be estimated as Ms = 7.2−7.6, using correlation relationships of Lunina and Gladkov (2015). It should be noted that the use of these correlations has several general limitations (Lunina and Gladkov, 2015): a) a relatively limited set of 36 sites, which includes neptunian dikes in addition to injection dikes; b) this approach does not take into account the geotechnical conditions at the sites; c) the sizes of the dikes depend on the epicentral distance. In our case, the sizes of the discovered dikes are also included in this set of limitations. The dikes widths used for correlation relationships vary from 0.27 to 0.81 (63% of injection dikes have widths of 0.2 m), while in our case their width reaches 0.9 m; c) the maximum visible height of the dikes used for correlation relationships reaches 1.82 m, and in the Malyi Yaloman section – 2–2.5 m. Nonetheless, the I = X–XI paleoearthquake shaking intensity (MSK-64 macro-seismic scale) calculated using the correlation relationships of Lunina and Gladkov (2015) is in good agreement with the X–XI intensity on the ESI 2007 scale indicated by the sizes of the SSDS (Guerrieri, 2015). These values are close to the largest known magnitude and intensity of events in Gorny Altai and its surroundings. Therefore, the epicentral area of the Holocene earthquake may fall within the Yaloman Basin.

The damage to burial mounds at the Chultukov Log 1 site can provide exact constraints neither on the magnitude and shaking intensity nor on the location of the event. However, earthquakes that produce colluvium are known to be at least I = V on the ESI 2007 intensity scale (Guerrieri, 2015).

6.3. Seismic risk for the territory around the Katun Fault

The archaeoseismological investigations reported in this paper, as well as paleoseismological data from (Deev et al., 2012b) have not yet confirmed the supposition expressed in (Ulomov et al., 2016) that earthquakes with Mw up to 7.0 can be related to the northern part of the Katun Fault. Types and sizes of SSDS (Deev et al., 2012b) as well as the character of damage to the cairns of the Chultukov Log 1 necropolis allow us to say that for this region
earthquakes of I=V-VII on the ESI 2007 intensity scale are typical. On the contrary, the southern part of the Katun Fault was not even considered during seismic zoning as an active seismic-generating structure (Ulomov et al., 2016). However, our paleoseismological investigations indicate that it is the southern part of the Katun Fault that is able to generate events with I=X-XI. These conclusions are very important, as it is along the southern side of the Katun Fault that a gas pipeline to China is planned to be built. No doubt, the obtained estimates must be taken into account during the planning and building of the gas line.

6. Conclusions

Synthesis of our paleoseismological and archaeoseismological data from the Katun Fault area, a major active fault zone in Gorny Altai, leads to the following main inferences.

1. Signatures of SSDS (seismites) found in the Yaloman and Manzherok basins indicate that the Katun Fault in Gorny Altai has been seismically active in the Middle Pleistocene-Holocene.
2. Gravel diapirs and sand dikes found near the Malyi Yaloman mouth mark the epicentral area of an earthquake that occurred after 12.5 ka (Mw=7.2 e 7.6, I=VII-XI) in the Yaloman Graben.
3. The southern end of the Katun Fault generated M/C21 5.0 e 5.5 (I/C21 VI-VII) earthquakes 150 and 90 ka BP, as well as several events in the 38 e 19 ka (with a recurrence time of ~2000 years) and 19 e 12.5 ka intervals.
4. Damage to exterior and interior elements of burials in the Chultukov Log 1 necropolis from the Manzherok Basin (northern end of the Katun Fault) results from surface ground motion and downhill sliding of colluvium caused by an earthquake of at least I=V that occurred in the time interval between the 3rd century BC and the 1st century AD.
5. The reported data is evidence of a greater seismic risk for the territory around the Katun Fault, which has to be taken into...
account in the design of the gas pipeline to China and touristic infrastructure.

Funding

The study was funded by the Russian Foundation for Basic Research, project No. 18-05-00389. The archaeological research was supported by the Russian Science Foundation, project No. 14-50-00036.

Acknowledgments

We wish to thank S. Kotler, Yu. Ryapolova, E. Lobova, D. Nazarov, S. Deeve, for aid in the field. Thanks are extended to T. Perepelova (IGM SB RAS, Novosibirsk) for cooperation and helpful advice. The manuscript benefited much from the thoughtful review and valuable comments by Prof. Harvey Kelsey, Dr. Christoph Grützner, and two anonymous reviewers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2018.11.009.

References


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Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Deformation structures</th>
<th>Magnitude, Shaking intensity, I (ESI 2007)</th>
<th>Age</th>
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<tbody>
<tr>
<td>Multiple events</td>
<td>Eight deformed beds, 2.5–40 cm thick, in lacustrine granule and fine pebble, outsize sand, and silt. Flame, ball-and-pillow structures and load casts.</td>
<td>≥5–5.5</td>
<td>VI–VII</td>
</tr>
<tr>
<td>Single event</td>
<td>Systmes of rootless fractures and micro-faults of slip amount within 20 cm, flexures, and convolute lamination in alluvial gravel.</td>
<td>≥5–5.5</td>
<td>VI–VII</td>
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<tr>
<td>Multiple events</td>
<td>Up to eleven deformed beds, 0.5–145 cm thick, in lacustrine sand, silt, and angular granule. Flame and ball-and-pillow structures; load casts; sand diapirs; pseudonodules;</td>
<td>≥5–5.5</td>
<td>VI–VII</td>
</tr>
<tr>
<td>Single event</td>
<td>with underlying lacustrine silt and sand.</td>
<td></td>
<td></td>
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<tr>
<td>Yaloman Graben, M.</td>
<td>Normal and reverse faults (up to 0.5 m dip slip) in soft sediments. Liquefaction-like SSDS</td>
<td>≥5–5.5</td>
<td>VI–VII</td>
</tr>
<tr>
<td>Yaloman Graben, M.</td>
<td>where some coarse gravels sink into underlying soft material. 7.7 km farther southeast: flame structures and load casts, up to 0.5 m high, produced by mixing of alluvial gravel with underlying lacustrine silt and sand.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yaloman Graben, M.</td>
<td>Alluvial gravel mixed with overlying overbank sand, and slope-wash deposits.</td>
<td>7.2–7.6</td>
<td>X–XI</td>
</tr>
<tr>
<td>Yaloman Graben, M.</td>
<td>Gravel diapirs, up to 2–3 m high, injected into overlying slope-wash deposits (locally all thickness through). Crushed slope-wash deposits and silt and sand dikes (up to 0.9 m thick and 2.5 m high). Faults with slip amount within a few tens of cm. 7.7 km farther southeast: gravel diapirs, up to 1 m high, produced by mixed sediments of similar grain sizes.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yaloman Graben, M.</td>
<td>Collouvium damaging burial mounds near mountain slope. Colluvial blocks scattered over 25 m from the slope that damage cairns, crepidomes, interior grave elements (boxes, box ceilings, inner walls), and anatomic order of bodies, including in burials not affected by colluvium from outside.</td>
<td>≥V</td>
<td>3rd century BC</td>
</tr>
</tbody>
</table>