Catastrophic outburst and tsunami flooding of Lake Baikal: U–Pb detrital zircon provenance study of the Palaeo-Manzurka megaflood sediments

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ABSTRACT
Lake Baikal, the largest freshwater reservoir on Earth (~600 × 30 km in size and up to 1.6 km in depth), has more than 300 contributing rivers but only one N-trending outflow – River Angara. In the Pliocene or Pleistocene, another N-trending outflow operated through the Palaeo-Manzurka to Lena. Provenance analysis using U–Pb dating of detrital zircons from the Palaeo-Manzurka sediments demonstrates that the dominant source of the zircons was the lake deposits, while the contribution of zircons from local bedrocks was limited to about 8% only. Looking for an explanation of this, we propose a hypothesis that formation of the Palaeo-Manzurka sediments took place in association with a catastrophic mega-landslide (~15 × 3 km) into the lake and the resulting mega-tsunami flooding.

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Introduction
Extreme events are rare and thus difficult to study. At the same time, they are very important for our understanding of how geological processes work and for assessment of potential hazards (McGuire 2006). Mega-tsunamis (waves >100 m; Goff et al. 2014) caused by landslides represent a good example of such extreme events. Mega-tsunamis were not widely recognized until rocks and ice fell into Lituya Bay (Alaska) on 9 July 1958 after an earthquake of magnitude 7.8–8.3 (Tocher and Miller 1959; Stover and Coffman 1993) followed by devastating waves up to 524 m in height (Miller 1960). Subsequently the idea of landslide-related mega-tsunamis with waves >100 m gained support from the study of gravel and exotic deposits in the Hawaiian Islands in the Pacific Ocean (Moore and Moore 1988). The mega-tsunami hazard was publicized, especially in terms of potential landslides in the Canary Islands and the resulting threat to the highly populated Atlantic Ocean coast (Ward and Day 2001). In some regions mega-tsunami records are indisputable (e.g. Lake Tahoe in the USA and Vajont artificial reservoir in Italy; see Moore et al. 2014; Barla and Paronuzzi 2013, respectively), but in many others are questionable (e.g. Bourgeois and Weiss 2009; Hutchinson and Attenbrow 2009). In this study, we analyse sedimentary deposits of a palaeo-outflow from Lake Baikal known under the name Palaeo-Manzurka river, and suggest a hypothesis that they were formed due to a catastrophic flooding event. Cataclysmic flooding of some large Siberian rivers is known due to their damming by glaciers and subsequent collapse (Rudoy and Rusanov 2005; Herget 2005; Komatsu et al. 2009, this issue; Margold et al. 2011), and also to subglacial volcanic eruptions and associated meltdown events (Komatsu et al. 2007). However, in the case of the Palaeo-Manzurka we provide evidence for previously undiscovered potential mechanisms of cataclysmic flooding of Siberian rivers in connection with a potentially massive landslide into Lake Baikal and the resulting mega-tsunami event.

General geological situation
The central part of the Baikal rift, which is occupied by waters of Lake Baikal, is situated between the Siberian Craton to the north and accreted Palaeozoic and Mesozoic terrains to the south (Figure 1). Thus contribution of sediment to the lake from these two directions should be different in terms of their chemical composition and, particularly, their age.

As revealed by 10Be dating of lacustrine sediments recovered from the underwater Academicichesky ridge
during international Baikal drilling project campaigns in 1996 and 1998 (BDP-96, BDP-98), Lake Baikal has existed in its modern extent for more than 8.4 million years (Horiuchi et al. 2003), which makes it not only the largest freshwater reservoir on Earth in terms of volume, but also the oldest. Prior to that, there was probably a smaller lake in the shape of the southern and central depressions, whose existence is evident from more than 9 km of sedimentary infill (Scholz and Hutchinson 2000).

Figure 1. (a) General tectonic subdivision of the region around Lake Baikal and drainage pattern of the Selenga and other rivers. Major tectonic units are simplified from Gladkochub et al. (2013). Neopr., Neoproterozoic. (b) Simplified geological map around southern Lake Baikal. The map is modified after Malitch (1999). Underwater relief of the Selenga delta is shown after The INTAS Project 99-1669 Team (2002). The dashed black line denotes underwater remnants of a giant landslide (see text). The Palaeo-Manzurka is shown after Kononov and Mats (1986) (see also Figure 2). S1, S2, and S3 (Selenga sites 1, 2, and 3, respectively), G (Goloustnaya), and KS (Kosaya Steppe) are study sites from which detrital zircons were collected for the U–Pb dating. Kh (Kharbatovo), site with large granite boulders (Figure 3); B (Biryulki) and A (Anga), sites with Palaeo-manzurka alluvium covered by typical Lena alluvium (Figure 4); U (Ushakovka formation) and K (Kachergat formation), sites with dated detrital zircons from Neoproterozoic sedimentary bedrocks (Gladkochub et al. 2013). (c) A cross-section showing the Palaeo-Manzurka alluvium in the modern relief, modified after Kononov and Mats (1986). The topographic cross-section follows the Palaeo-Manzurka channel, shown as the dashed brown line in (b).
the major inflow is the Selenga river, which drains an area underlain mainly by Palaeozoic and Mesozoic rocks (Figure 1a). Sediments from these rocks include minerals resistant to weathering such as zircons, and these are deposited in Lake Baikal at the Selenga delta fan, which extends practically across the lake underwater (The INTAS Project 99–1669 Team 2002). Despite the fact that Lake Baikal is very old, the modern outflow – the Angara river flowing northward – is a recent feature. The Angara outlet was created by rapid tectonic subsidence of a block of basement at Listvenichny Bay (Kononov and Mats 1986; Mats et al. 2002). The precise timing for the Angara outflow is unknown, but it was estimated by molecular dating of gammarids as about 60 ka (Mashiko et al. 1997), and of fishes as about 50–400 ka (Koskinen et al. 2002; Froufe et al. 2008). Prior to this outflow, there were other outflows: (1) the Palaeo-Kultuchnaya river drained along the modern Kultuchnaya towards the Irkut and then to the Angara; and (2) the Palaeo-Manzurka drained towards the Lena through the Precambrian to early Cambrian complexes of the Siberian craton (Kononov and Mats 1986) (Figure 1b). The existence of the Palaeo-Kultuchnaya outflow is rejected by some researchers, however (e.g. Ufimtsev et al. 2010).

The Palaeo-Manzurka outflow has never been questioned. The palaeo-river channel is still evident in the modern relief (Figure 2), having been identified by tracing unusually yellow-coloured sediments (Figures 3 and 4) within dominantly red-coloured early Cambrian complexes from Lena up to the Primorsky Range composed of Precambrian rocks, and then up to shore of Lake Baikal through these (Figure 1b). Sedimentary deposits of the Palaeo-Manzurka became a dilemma for regional geology from the time of their identification (Logachev et al. 1964, 1974), including the yet-unsolved problem of their age, which might be the Pliocene (Zamaraev et al. 1976) or Pleistocene (Trofimov et al. 1999). Even so, the connection of the Palaeo-Manzurka and Baikal is unquestioned and no typical Baikalian diatoms were found in Palaeo-Manzurka sediments (Logachev et al. 1964; Trofimov et al. 1999).

The most prominent Palaeo-Manzurka sedimentary deposits are traced along the modern Manzurka river, which flows north and joins the Lena, and along the Buguldeika and Goloustnaya rivers, both of which flow today in opposite directions and enter Lake Baikal (Figure 1b, c). A profile along the reconstructed valley of the Palaeo-Manzurka is shown in Figure 1c. Interestingly, the Palaeo-Manzurka sediments are located 50–400 m higher than the present-day level of Lake Baikal. One explanation involves outflow via the Palaeo-Manzurka towards the Lena, and suggests that the level of Lake Baikal was higher in the geological past (Kononov and Mats 1986; Mats 1993; Mats et al. 2002). An alternative interpretation is that the Primorsky Range was lower, and the absolute water level of Lake Baikal stayed similar to its present-day level (Colman 1998; Ivanov and Demonterova 2009).

![Figure 2](image-url)
The sedimentary deposits of the Palaeo-Manzurka are typically horizontally layered with boulders and pebbles at their lower parts and mainly sandy upper parts of the cross-sections (Figure 5), similar to those accumulated by megafloods (Carling 2013). These deposits often contain erratic, sharp-edged blocks and rounded boulders of Precambrian rocks. For example, granite boulders up to 1 m in diameter and above were found within Palaeo-Manzurka sediments near Kharbatovo (Figure 3) about 100 km downstream from their potential source (Figure 1c). This observation raises the question of transport mechanism of such large boulders over such a distance. The Hjulström diagram predicts that to move a boulder of diameter 1 m by river flow, the velocity of that flow must be ~8 ± 1 m s⁻¹ (Sundborg 1956), which is two- to threefold higher than the highest water speed ever measured for the Lena (3.0 m s⁻¹ during the 1936 flooding) or the Manzurka (2.4 m s⁻¹ during the 1966 flooding) (Konovalova 1949; Borisova 1968). Such boulders could, in principle, be glacially transported. However, all glaciers were concentrated to the east within the high mountain framing of northern Lake Baikal (Figure 2). The region near Kharbatovo is located too distant from high mountains and at altitudes too low for glaciation (e.g. Osipov and Khlystov 2010).

Another unresolved question is the occurrence within the Palaeo-Manzurka deposits of pebbles whose composition matches that of Mesozoic volcanic rocks originally distributed south of Lake Baikal (named Transbaikalia), and redeposited in the cratonic region north of Lake Baikal in the form of Jurassic conglomerates (Logachev et al. 1964, 1974). Both regions
(Transbaikalia and Jurassic conglomerates), however, are not within the expected drainage area of the Palaeo-Manzurka (Figure 1). An *ad hoc* assumption was made that during the time of the Palaeo-Manzurka activity the Jurassic conglomerates were abundant within its drainage area, but were completely eroded and with no signs of such deposits remaining (Logachev *et al.* 1964, 1974; see discussion below).

Yet another overlooked problem is the distribution of the Palaeo-Manzurka-type deposits upstream in the rivers Lena and Anga from the expected mouth of the Palaeo-Manzurka (which is essentially the same as that of the present day Manzurka) (Figures 1b and 2).

*Figure 4a* shows a terrace on the right bank of the Lena river near Biryulki (see Figures 1 and 2 for location), where the typically yellow Palaeo-Manzurka sediments (about 18 m thick) are covered by typically reddish Lena alluvium (3–3.5 m). The section is topped by fine-sized, whitish-coloured sediments of probably aeolian origin, which are topped by Holocene soils. The significance of this section will be discussed later.

*Figure 4b* shows the Palaeo-Manzurka-type sediments at the Anga, which is a right-hand tributary of the Lena (Figures 1b and 2). This site was previously considered as evidence for the existence of another palaeo-river that went under the name Palaeo-Anga, which flowed to the Lena from the east (Logachev *et al.* 1974). However, this was an *ad hoc* explanation for the unusual appearance of yellow-coloured sediments at Biryulki (a) and Anga (b). These sites are respectively about 10 km upstream of the Lena from the potential mouth of the Palaeo-Manzurka and about 10 km upstream of the Anga (Figures 1b, 2). At Biryulki, the yellow Palaeo-Manzurka sediments are covered by the reddish Lena alluvium, which is covered by aeolian sediments of the latest glaciation, which in its turn is covered by Holocene soils.
sediments found unexpected sites among red-coloured local alluvium (Figures 3 and 4).

**Samples and methods**

To resolve the question of how the Palaeo-Manzurka sediments were deposited, we collected sands from three sites within two sites – Goloustnaya and Kosaya Steppe (Figure 1b, c). At the Goloustnaya site we sampled the lower exposed part of the cross-section composed mainly of gravel and topmost sands; at Kosaya Steppe we sampled material from the lower part where boulders and pebbles were abundant (Figure 5). From these three samples (15–20 kg each) we collected numerous detrital zircon grains and dated 171 of these by the U–Pb method using laser ablation inductively coupled plasma–mass spectrometry (ICP-MS). As a reference for detrital zircons from the Selenga underwater delta, we also collected sands from three sites at the Selenga (Figure 1b). From these three samples 157 detrital zircon grains were dated by the same method. All zircon grains were in the range 120–250 μm. As a reference for detrital zircons from bedrocks we used published data for Neoproterozoic sediments (Gladkochub et al. 2013).

The sediment samples were processed for detrital zircon separation at the Institute of the Earth Crust SB RAS, Irkutsk, Russia. The samples were dried, sieved to fractions of 250–180 and 180–120 μm, and further separated by density using a water flow table. The dense fraction was processed through an electromagnet. Non-magnetic fractions were further separated by density using heavy liquids as described by Paton et al. (2010). Several thousand zircon grains were finally picked and manually cast in epoxy mounts, which were polished in order to section the crystals for analysis.

Zircon grains were imaged at the Institute of Earth Sciences Academia Sinica, Taipei, Taiwan using a scanning electron microscope (JEOL JSM-6360LV) with Gatan mini-CL detector by taking backscattered electron and cathodoluminescence images (Chiu et al. 2009). Zircon U–Pb isotope analyses were performed by ICP-MS using a New Wave UP213 laser and an Agilent 7500s quadrupole ICP-MS housed at the Department of Geosciences, National Taiwan University (Chiu et al. 2009). Zircons of all possible shape and type were analysed, while avoiding those with multiple cracks and/or inclusions. A spot size of 30 μm with laser repetition rate of 4 Hz was applied to all analyses, and the laser energy density used was ~15 J cm⁻².

Calibration was performed by using the zircon standard GJ-1 with a 207Pb/206Pb age of 608.5 ± 0.4 Ma (Jackson et al. 2004). Two well-known zircon standards, 91,500 and Mud Tank, with assigned ages of 1065.4 ± 0.6 Ma (207Pb/206Pb, ±2σ) (Wiedenbeck et al. 2004) and 608.5 ± 0.4 Ma (207Pb/206Pb, ±2σ) (Jackson et al. 2004), respectively, together with a new zircon standard Plešovice (337.1 ± 0.4 Ma; Sláma et al. 2008), were used for data quality control. Measured U–Th–Pb isotope ratios were calculated using GLITTER 4.4 (GEMOC) software, and the relative standard deviations of reference values for GJ-1 were set at 2%. The
common lead was directly corrected using the common lead correction function proposed by Andersen (2002), and the weighted mean U–Pb ages and concordia plots were carried out in ISOPLOT v. 3.0 (Ludwig 2003). Given that precise age analyses using $^{207}\text{Pb}/^{235}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios are usually feasible only for Precambrian zircons, $^{206}\text{Pb}/^{238}\text{U}$ ages are used for zircons <1 Ga and $^{207}\text{Pb}/^{206}\text{Pb}$ ages for those ≥1 Ga. U–Pb data and concordia diagrams are presented for each site in the supplementary file (see http://dx.doi.org/10.1080/00206814.2015.1064329).

Results

U–Pb dating of detrital zircon grains collected from the three sites of Palaeo-Manzurka deposits revealed similar ages between the Palaeo-Manzurka zircons and those collected from the Selenga river (Figure 5). All six major age peaks documented for zircons from the Selenga alluvium, which are typical for the Selenga drainage area (Donskaya et al. 2013), are reproduced for zircons from the Palaeo-Manzurka deposits (Figure 6). Special attention is given to Cretaceous zircons, which could be sourced only from the region south of Lake Baikal. An even more surprising feature, however, is that Palaeo-Manzurka sediments have only a small number of zircon grains (13 out of 171) with ages of 0.7–0.9 and 1.8–1.9 Ga, despite the fact that these are the typical ages for bedrock zircons (Figure 6) (i.e. these are the dominant detrital zircon population ages for Neoproterozoic sedimentary rocks (Gladkochub et al. 2013) and Palaeoproterozoic granites (Mazukabzov et al. 2001; Rojas-Agramonte et al. 2011), respectively. In other words, if the Palaeo-Manzurka outflow developed under the normal conditions of river, we would expect zircons of Precambrian age to be dominant whereas those of Palaeozoic or Mesozoic age should be strongly subordinate. Just the opposite was observed.

Discussion

Model of catastrophic outburst

To explain the inverse age relation (Figure 6), together with the unresolved issues discussed above, we suggest a catastrophic model for the origin of the Palaeo-Manzurka outflow. This catastrophic model is illustrated schematically in Figure 7. At some moment in time, the level of Lake Baikal relative to the northern areas was higher, but with no connection between the lake and the Palaeo-Manzurka due to the existence of a ridge.
We suggest that a basement block, perhaps 15 km × 3 km in size and located between Lake Baikal and upper reaches of the Palaeo-Manzurka, suddenly slid into the lake, probably as a consequence of a major earthquake. The remnants of the giant landslide are evident from both underwater relief and the character of the lake shoreline (Figure 8). The landslide is partially covered by the more recent Goloustnaya delta. Underwater topography of the landslide is well developed and resembles inland topography (Figure 8).

Shortened river lengths constrain the size of block removed from the shore (Figure 9). Interestingly, rivers

Figure 7. Schematic representation of a model for the catastrophic outburst of Lake Baikal waters through the Palaeo-Manzurka due to a giant landslide and followed by a mega-tsunami (stage 2). Stages 1 and 3 denote the pre-catastrophe time and the present, respectively.

Figure 8. Bathymetry map of the region of the supposed landslide (with minor modifications after Khlystov et al. 2014). Khlystov et al. (2014) interpreted the landslide as a palaeodelta of Goloustnaya covered by its modern deltaic sediments.

Figure 9. River lengths as a function of distance from the Goloustnaya mouth measured along the lake coastal line. Open symbols denote rivers developed in the framework of the underwater landslide boundaries. The sharp change in river lengths marks the SW boundary of the landslide. The shore to the northeast of the Goloustnaya mouth is characterized by renewed relief due to the sliding event.
are shortened not only at the Goloustnaya landslide area, but also when approaching Listvenichny Bay, where underwater landsliding is also recorded (Kononov and Mats 1986; Mats et al. 2002). A discussion of opening of the modern Angara outlet in association with the Listvenichny Bay sliding event is beyond the scope of this article, but we would like to stress that this process could also have been catastrophic.

A landslide 15 km × 3 km in size would create a mega-tsunami wave of the Hawaii type, when rocks slide into a deep-water basin and create a depression in the water which is later filled by waters creating a large wave precisely where the block slid (McMurtry et al. 2004). The Lituya-type mega-tsunami resulted from rock sliding into a shallow basin, with tsunami wave propagation away from the impact region (Fritz et al. 2009). For example, a historic mega-tsunami event in the 200 m-deep Vajont artificial reservoir in Italy, with maximum wave height of 235 m (Panizzo et al. 2005), was of the Lituya type. The palaeo mega-tsunami at the 500 m-deep Lake Tahoe in the USA (e.g. Moore et al. 2014) may have been transitional between the Lituya and Hawaii types.

We do not know whether this landslide event on its own opened the way for Lake Baikal waters to Palaeo-Manzurka or the mega-tsunami wave carried the rocks through, establishing the outflow pattern to the Lena. Obviously, the Palaeo-Manzurka sediments were deposited rapidly because of flooding associated with the catastrophic outburst of Lake Baikal (Urabe et al. 2004). The top figure shows the relative drop in water level during marine isotope stages (MIS) 5 and 3.

Timing of the event

The timing of the landslide into Lake Baikal is not yet known, and this part of the article is the most speculative. Certainly, the Palaeo-Manzurka was formed before the formation of the modern Angara outlet, estimated approximately between 400 and 50 ka (Mashiko et al. 1997; Koskinen et al. 2002; Froufe et al. 2008) and after the formation of the large water basin of Lake Baikal, which has existed for at least 8.4 million years (Horiuchi et al. 2003). Traditionally the age of the Palaeo-Manzurka sediments was estimated as Pliocene on the basis of rare findings of pollens and animal teeth (Logachev et al. 1974; Zamaraev et al. 1976). Direct dating by thermoluminescence (TL) (Trofimov et al. 1999) shows the Pleistocene age of the Palaeo-Manzurka sediments. Due to their inconsistency with the conventional point of view of Pliocene age, the TL results of Trofimov et al. (1999) were rejected by local geologists as unreliable. However, here we argue that the TL ages should be seriously considered and that there is evidence in support of a Pleistocene age for the Palaeo-Manzurka megaflood sediments.

Figure 10 shows the TL ages recalculated in the form of a probability age histogram. This shows a distinct peak at either 117 ± 28 or 126 ± 24 ka if the youngest and oldest TL ages are rejected. Either of these two values overlap within their large error bars with the timing of a 40 m drop in the water level of Lake Baikal, as having happened during the marine oxygen isotope stage (MIS) 5 on the basis of seismic profiling (Urabe et al. 2004). If this water level drop is associated with the outburst flooding of the Palaeo-Manzurka, then the second 10–20 m water drop at MIS 3 is logically attributed to catastrophic outburst flooding of the Angara. It should be mentioned that Urabe et al. (2004) favoured the palaeoclimatic explanation for the water level changes.
Another interesting feature is that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in both terrigenic and diatom sediments of Lake Baikal increased rapidly at about 100 ka from the present-day water value of about 0.7088 (Falkner et al. 1997) to 0.7097 in the diatoms and to 0.713 in the terrigenic sediments (Kuzmin et al. 2007). Kuzmin et al. (2007) interpreted such an increase as evidence of a catastrophic earthquake, which brought to the lake significant amounts of terrigenic material. As an analogue they referenced the 1861 earthquake which formed Proval Bay (Figure 1b).

Still further evidence of a relatively young age for the Palaeo-Manzurka alluvium comes from a site near Biryulki (Figure 4a). There the Holocene soils cover typically whitish aeolian sediments of the latest glaciation, covering the Lena alluvium which covers the Palaeo-Manzurka megaflood sediments. If the Palaeo-Manzurka sediments were Pliocene as traditionally considered (Logachev et al. 1974; Zamaraev et al. 1976), we would expect to find a more complex pattern of sedimentation in that site.

Taking the foregoing into consideration, we maintain that all such theories should be tested using a special geochronological study of the Palaeo-Manzurka megaflood sediments, which is a future project.

**Alternative explanations**

**The Palaeo-Manzurka was part of the Selenga river**

The first theory worth considering in light of the results obtained for detrital zircon age distribution (Figure 6) is that the Palaeo-Manzurka was the lower stream of the Selenga river before formation of the southern and central depressions of Lake Baikal. However, we reject this explanation for a number of reasons. First, despite the fact that this would explain similarities in age distribution of zircons from both the Palaeo-Manzurka and Selenga deposits, it does not explain the virtual absence of a local ‘cratonic’ signal in the former (Figure 6). Second, as mentioned above, Lake Baikal has a history of at least 8.4 million years of water-filled basins (Horiuchi et al. 2003), whereas all estimations of the age for Palaeo-Manzurka sediments suggest that the Palaeo-Manzurka is significantly younger (see discussion above). Third, even if the water-filled basins were younger or the Palaeo-Manzurka sediments were older than estimated, the southern and central depressions are the oldest in the Baikal rift – these may be as old as Eocene (see review by Ivanov et al. 2015). Thus it is highly unlikely that the Selenga river could have gone through these depressions keeping only Transbaikalian zircons without collecting a significant proportion of cratonic zircons.

**Palaeo-Manzurka sediments from Jurassic sediments**

The link between Palaeo-Manzurka sediments and Jurassic conglomerates was suggested by Logachev et al. (1964, 1974) on the basis of findings of abundant Mesozoic pebbles in Palaeo-Manzurka deposits. Our field observations support these earlier findings. Logachev et al. (1964, 1974) suggested that the Palaeo-Manzurka deposits had inherited material from Jurassic conglomerates during a normal development of the Palaeo-Manzurka river. Jurassic conglomerates were initially located along the Palaeo-Manzurka channel according to this interpretation. One key observation contradictory to this interpretation is the finding of Cretaceous zircons in Palaeo-Manzurka sediments (Figure 6) that could not be emplaced into the sedimentary deposits if the Palaeo-Manzurka river had simply reworked Jurassic conglomerates. An additional source of Cretaceous (Transbaikalian) zircons is required, which according to our interpretation is the Selenga delta.

To explain Mesozoic pebbles in the Palaeo-Manzurka megaflood deposits, we assume that Jurassic conglomerates were also located on top of the slide block and were thus extended from the current outcrop area at the shore of Lake Baikal (Figure 1b) for about 15 km northeastward. Relatively loose conglomerates were washed out by the mega-tsunami into the Palaeo-Manzurka and deposited there.

**High-water level of Lake Baikal**

Our model requires a high-water level for Lake Baikal at the time of the sliding event (Figure 7). A number of high terraces have been recorded on the shores of Lake Baikal (Kononov 2005), this being interpreted either from the point of view of previous high-water levels (e.g. Mats et al. 2002) or tectonic uplift (e.g. Colman 1998). We favour the former interpretation based on the fact that on Bolshoi Ushkanii Island (see Figure 2 for location) 10 terraces have been recorded, with the highest 216 m above the present level of Lake Baikal (Lamakin 1952). In addition to higher terraces, underwater terraces have been also recorded, supporting a low level of Lake Baikal at beginning of MIS 2 (Osipov and Khlystov 2010). An additional study of Lake Baikal terraces is required, however.

**Conclusions**

Provenance analysis using U–Pb ages of detrital zircons from the Palaeo-Manzurka sediments provides strong evidence for its formation due to a geological catastrophe associated with a giant landslide that created outburst flooding of Lake Baikal.
The modern outlet from Lake Baikal, the Angara, was formed due to tectonic subsidence of a block of basement, and this process could also have been catastrophically rapid.

The potential likelihood for future landslides and associated tsunamis in Lake Baikal should be seriously assessed in regard to densely populated areas both on the lake shores and along the Angara river.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed at http://dx.doi.org/10.1080/00206814.2015.1064329.

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