Quaternary Research 76 (2011) 393–396

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Short Paper

Glacial Lake Vitim, a 3000-km^3 outburst flood from Siberia to the Arctic Ocean

Martin Margold *, Krister N. Jansson, Arjen P. Stroeven, John D. Jansen

ARTICLE INFO

Article history:
Received 22 February 2011
Available online 4 August 2011

Keywords:
Glacial lake outburst flood (GLOF)
Freshwater influx
Transbaikalia
Ice-dammed lake

ABSTRACT

A prominent lake formed when glaciers descending from the Kodar Range blocked the River Vitim in central Transbaikalia, Siberia. Glacial Lake Vitim, evidenced by palaeoshorelines and deltas, covered 23,500 km^2 and held a volume of ~3000 km^3. We infer that a large canyon in the area of the postulated ice dam served as a spillway during an outburst flood that drained through the rivers Vitim and Lena into the Arctic Ocean. The inferred outburst flood, of a magnitude comparable to the largest known floods on Earth, possibly explains a freshwater spike at ~13 cal ka BP inferred from Arctic Ocean sediments.

Introduction

Pleistocene glacial lakes formed where glacier or ice-sheet margins obstructed natural drainage routes (Upham, 1896; Mangerud et al., 2001, 2004). The failure of such dams triggered catastrophic outburst floods, and those from glacial lakes Missoula (northwestern USA) and Chuja–Kuray (southern Siberia) count amongst the greatest known floods on Earth (Waitt, 1985; Baker et al., 1993; Herget, 2005; Table 1). Furthermore, large meltwater fluxes, like those stemming from the sudden drainage of North American glacial lakes during late glacial times, are thought to have triggered shifts in ocean circulation that propagated major climate changes on a global scale (Barber et al., 1999; Teller et al., 2002; Tarasov and Peltier, 2005; Broecker, 2006). In this pilot study, based on a GIS analysis of remotely sensed data, we argue for the occurrence of a large glacial lake outburst flood in a remote and little-researched region of Siberia.

The outlines of glacial lakes and drainage diversions created by outburst floods are relatively well known from North America, western Eurasia, and the Himalayas (e.g., Waitt, 1985; Leverington et al., 2000, 2002; Mangerud et al., 2001; Montgomery et al., 2004; Herget, 2005; Jakobsson et al., 2007; Komatsu et al., 2009; Wiedmer et al., 2010). Far less is known of the mountains of central and eastern Siberia. The Transbaikalia region, east of Lake Baikal, supports only a few small contemporary glaciers, and the existing knowledge of the character and extent of former glaciation is limited and contradictory (Shahgedanova et al., 2002; Enikeev, 2009). Yet, evidence of former alpine glaciers descending into large extensional intermontane basins with narrow outlets fuels potential for major ice dams in the Pleistocene.

In the River Vitim catchment (Fig. 1), well-preserved deltas and palaeoshorelines occur at concordant elevations around the Muya–Kuanda depression and upstream. The existence of a glacial lake in the Vitim area was suggested by Grosswald and Rudoy (1996) and described by Krivonogov and Takahara (2003), Enikeev (2009, in Russian), and Margold and Jansson (2011); however, the configuration of the damming glaciers and the outburst chronology is yet to be documented. Here, building on a recently conducted remote-sensing mapping survey (Margold and Jansson, 2011), we provide the dimensions of Glacial Lake Vitim, inferences on the ice-dam configurations, and geomorphological evidence for the passage of a catastrophic outburst flood that possibly compared with the largest known floods on Earth. We postulate that the magnitude of this flood was sufficiently large to have caused far-reaching climatic and environmental impacts connected with large freshwater influx to the Arctic Ocean. Sediment core PS2458 from the Laptev Sea analysed by Spielhagen et al. (2005) reveals an 'outstanding' $\delta^{18}O$ spike at ~13 cal ka from freshwater runoff. The source of the freshwater influx remains unknown, but we argue that Glacial Lake Vitim is a strong candidate.

Glacial Lake Vitim

North of the Muya–Kuanda depression, the River Vitim cuts a narrow valley through the Northern Muysk Range (Fig. 1). It has been suggested that a valley glacier emanating from the Kodar Mountains blocked the River Vitim beyond present-day Lake Oron (Fig. 2), creating a glacial lake (Krivonogov and Takahara, 2003; Margold and Jansson, 2011). This case, in which a valley glacier from the Lake Oron tributary formed a dam, represents the most restricted ice configuration leading to the formation of Glacial Lake Vitim. Another significantly more extensive configuration of damming glaciers is inferred for the area downstream of the Lake Oron tributary where interconnecting valleys indicate the development of a network of confluent valley glaciers that blocked the Vitim valley. The blocking ice probably filled the Vitim valley for some distance, as shown by the U-shaped valley profile that extends downstream from this

* Corresponding author at: Department of Physical Geography and Quaternary Geology, Stockholm University, 106 91 Stockholm, Sweden. Fax: +46 8164818.
E-mail address: martin.margold@natgeo.su.se (M. Margold).

0033-5894/$ – see front matter © 2011 University of Washington. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.yqres.2011.06.009

Table 1
Dimensions of selected glacial lakes and Lake Baikal.

Name	Area [10^3 km^2]	Volume [10^3 km^3]	Source
Glacial lakes dammed by mountain glaciers			
Glacial Lake Vitim	23.5	3.0	This paper
Chuja–Kuray palaeolake (Altai Mts., Siberia)	2.6	0.8	Herget, 2005
Darkhadyn Khotgor (Sayan Mts., Siberia)	3.3	0.4	Komatsu et al., 2009
Tsangpo River (Tibet)	2.8	0.8	Montgomery et al., 2004
Glacial lakes dammed by ice sheet lobes			
Lake Missoula (northwestern USA)	7.5	2.2	O'Connor and Baker, 1992; Baker, 2007
Lake Atna (Alaska)	8.9–24.0	2.3–6.0	Wiedmer et al., 2010
Glacial lakes dammed by ice sheets			
YG Baltic Ice Lake	349.0	29.0	Jakobsson et al., 2007
Lake Agassiz; Campbell stage	263.0	22.7	Leverington et al., 2000
Lake Agassiz–Ojibway	841.0	163.0	Leverington et al., 2002
Lake Komi	76.0	2.4	Mangerud et al., 2001
Lake in White Sea Basin	218.0	15.0	Mangerud et al., 2001
Lake on West Siberian Plain	613.0	15.0	Mangerud et al., 2001
Present-day lakes			
Lake Baikal	31.7	23.6	The INTAS Project 99-1669 Team, 2002

confluence area (Margold and Jansson, 2011). Distinct and extensive palaeoshorelines indicate a maximum lake level of 840 m a.s.l. (Margold and Jansson, 2011), which corresponds to a col in the southeast (yellow arrow, Fig. 1b) through which Glacial Lake Vitim overflowed to the River Nercha (Enikeev, 2009).

Glacial Lake Vitim filled the entire Muya–Kuanda depression and branched into tributary valleys (Fig. 1). The chronology of the lake remains unresolved. Enikeev (2009) suggested that the timing of the lake is framed by a single radiocarbon date of 24,730 ± 770 ^{14}C yr BP (SOAN-2979) on a piece of wood underlying lacustrine sediments, and archaeological remains from the area that are approximately 12 ka (Vetrov, 1995 in Enikeev, 2009). However, the existence of more than a single lake phase is also suggested by two lacustrine units, exposed in a cut bank of the Muya River, which are separated by a palaeosol radiocarbon dated to 40,500 ± 930 ^{14}C yr BP (SOAN-2893) and 38,320 ± 755 ^{14}C yr BP (SOAN-2823, Krivonogov and Takahara, 2003). Based on a GIS analysis of the Shuttle Radar Topography Mission data (spatial resolution 3-arc seconds, 50–90 m), we calculate the lake area to have been 23,500 km^2, with a volume of ~3000 km^3, and maximum depth of 490 m near the ice dam (figures relate to the 840-m threshold-controlled level of the lake). Taking the present-day estimated mean annual discharge of 1125 m^3/s (R-ArcticNET v4.0, 2010) for the River Vitim at Nelyaty (Fig. 1b), lake filling would have taken approximately 85 yr; however, this is a minimum estimate given that the regional climate was probably significantly drier during glacial periods (Shahgedanova et al., 2002).

Catastrophic drainage

Multiple large-scale erosional features, consistent with the work of a high-magnitude outburst flood, occur within the study area. The most spectacular example occurs 15 km downstream from Lake Oron, where a canyon is perched on the eastern slope ~100 m above the

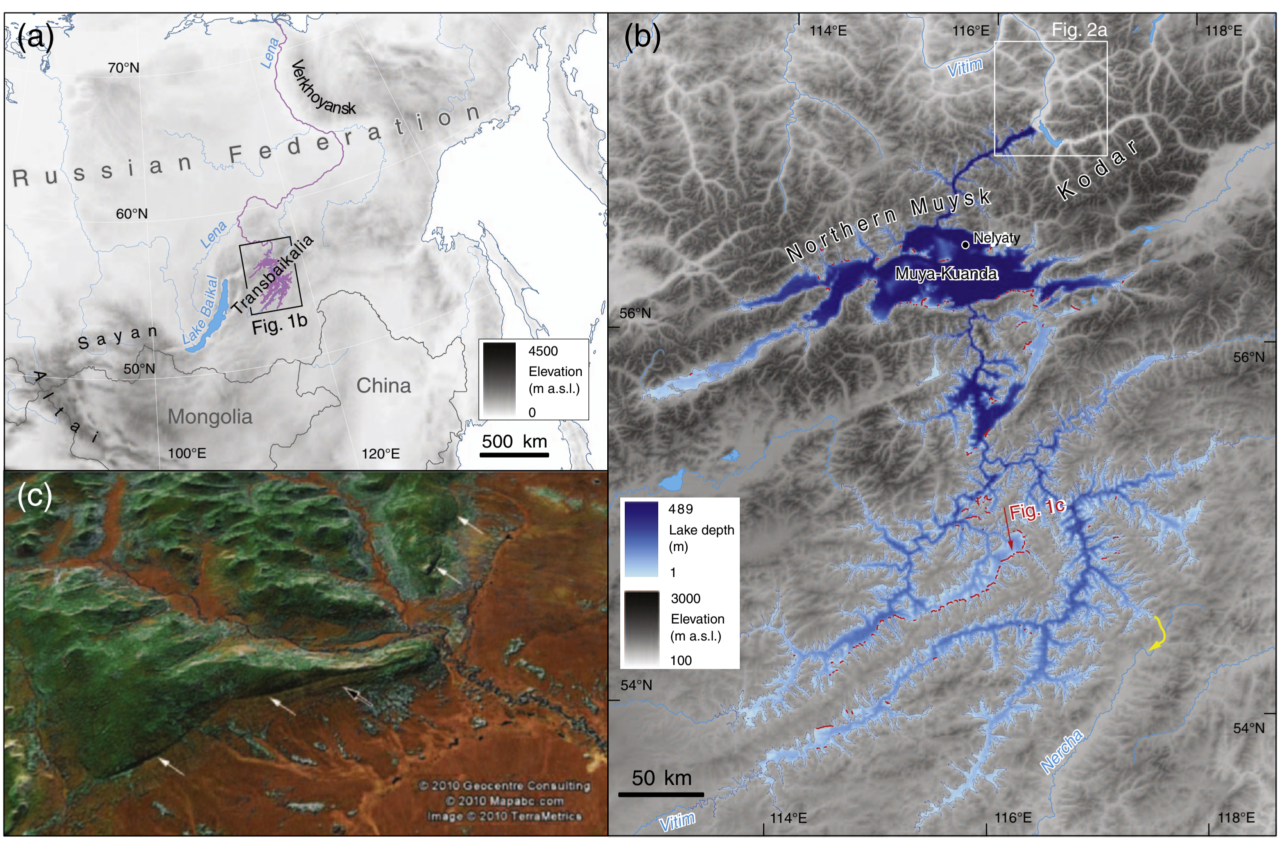

Fig. 1. (a) Location of Glacial Lake Vitim (pink) and the postulated outburst flood path to the Arctic Ocean. (b) Glacial Lake Vitim (Margold and Jansson, 2011); the depth of the lake is indicated by shades of blue. The lake was deepest (490 m) at the glacier dam in the area marked by the white square expanded in Fig. 2a. Indicated are palaeoshorelines (red lines) and the overflow col to the River Nercha (yellow arrow). (c) The oblique Google Earth view displays the distinct 840 m a.s.l. shoreline at the maximum lake level (white arrows), and a lower, local shoreline (black arrow); the location of these shorelines is denoted in panel b.

https://doi.org/10.1016/j.yqres.2011.06.009 Published online by Cambridge University Press

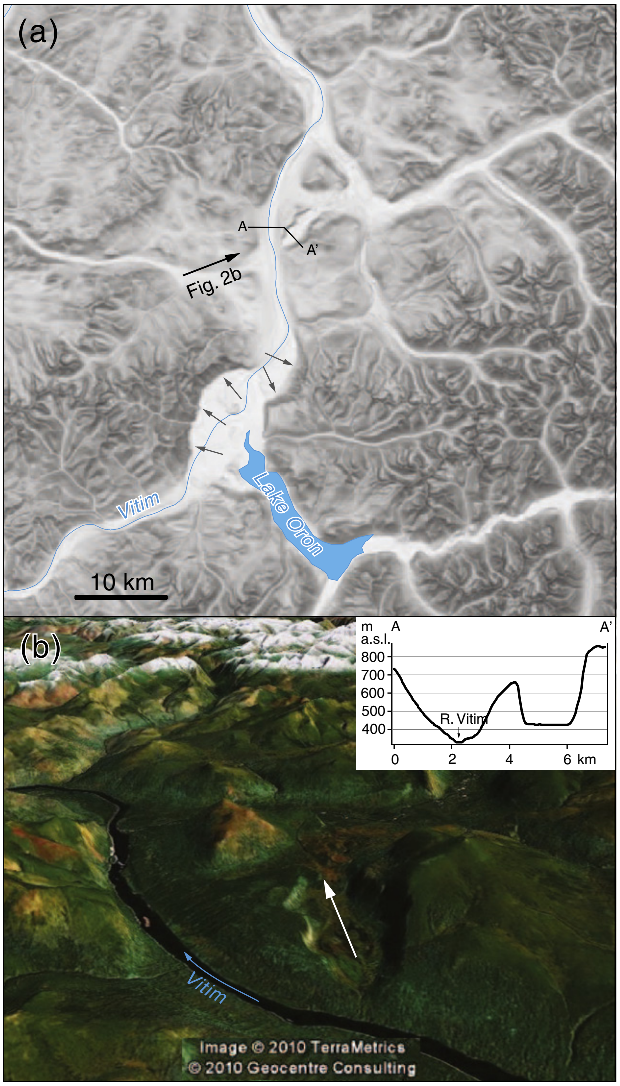

Fig. 2. (a) The surroundings of the postulated ice dam (see Fig. 1b for location). At the minimal ice configuration, the lake was dammed by a glacier emanating from the valley that is today occupied by Lake Oron. Anomalous steep escarpments suggestive of catastrophic erosion are indicated by small gray arrows. The viewing angle of the canyon portrayed in panel b is indicated by the large arrow, as is the location of the cross-section A–A′. Note the apparent glacial modification of valleys surrounding the canyon. (b) The large perched canyon (axis marked by white arrow) and its cross-section (upper right corner) were probably formed when Glacial Lake Vitim was drained during a catastrophic outburst flood.

present-day River Vitim (Fig. 2). The canyon is 300 m deep, 2 km wide and 6 km long, and is unrelated to the existing drainage pattern. We postulate that the canyon was formed by fluvial erosion when the lake drained catastrophically after the failure of the ice dam. Anomalous large-scale erosion also occurs at the junction with the Lake Oron tributary where the expanded main Vitim valley is flanked by steep escarpments standing ~1300 m high on the western slope, and ~1000 m high on the eastern slope facing the next bend downstream (Fig. 2). Both escarpments display evidence of hillslope trimming without significant talus accumulations, which is consistent with outer-bend fluvial erosion during high-magnitude floods (e.g., Herget, 2005). We suggest future studies should search for flood-related landforms in the lower Vitim valley; unfortunately, the spatial resolution of existing remotely sensed data is inadequate for such detailed geomorphological mapping.

The postulated outburst flood followed the River Vitim into the Lena River, and then into the Laptev Sea and the Arctic Ocean (Fig. 1). The estimated ~3000 km^3 flood (a maximum value assuming the lake drained completely from the 840-m shoreline) equals approximately six years' runoff from the present-day Lena River (Spielhagen et al., 2005; R-ArcticNET v4.0, 2010), or the annual runoff from all circum-Arctic rivers combined (Aagaard and Carmack, 1989).

Environmental impacts

We postulate three significant environmental impacts of Glacial Lake Vitim, which should be tested by further work in this area. First, the presence of a large water body may have influenced local climate, just as large glacial lakes at the southern margin of the Barents–Kara Ice Sheet imposed positive feedbacks on glacier mass balance and stimulated ice-sheet growth (Krinner et al., 2004). Second, the rapid demise of the lake and the pulse of floodwater possibly caused severe erosion and deposition along the Vitim valley, perhaps extending as far as the Lena delta. Third, the up to 3000-km^3 pulse of freshwater could have provoked regional-scale shifts in sea-water composition, climate, ocean circulation and the pattern of sea-ice build-up in the Arctic Ocean. Sediments from core PS2458 from the Laptev Sea indicate a short period of profound changes in salinity during the last deglaciation due to large freshwater pulses (Spielhagen et al., 2005). Spielhagen et al. (2005) tentatively ascribed these freshwater influxes to outburst floods from glacial lakes formed when glaciers from the Verkhoyansk Mountains (Fig. 1a) dammed the Lena River. Here, we propose an alternative hypothesis, in which a large outburst flood from Glacial Lake Vitim was responsible for this major influx of freshwater to the Arctic Ocean.

Conclusions

Glacial Lake Vitim in Transbaikalia, Siberia, was formed when glaciers descending from the Kodar Range blocked the River Vitim. The lake was significantly larger (volumetrically) than glacial lakes Missoula (northwestern USA) and Chuja–Kuray (southern Siberia), from which the currently largest-known outburst floods have been documented. Geomorphological evidence in support of an outburst flood exists in the area of the inferred ice dam, the most prominent being a 300-m-deep canyon on the eastern slope of the Vitim valley. Glacial Lake Vitim and its demise probably influenced climate and environment on a local and regional scale, and may possibly explain the major freshwater influx previously identified from sedimentary evidence in the Laptev Sea, Arctic Ocean.

Acknowledgments

We thank Chris Clark, anonymous reviewer and editors Jim O'Connor and Derek Booth for their constructive comments on the earlier version of the manuscript.

References

Aagaard, K., Carmack, E.C., 1989. The role of sea ice and other fresh water in the Arctic circulation. Journal of Geophysical Research 94, 14485–14498.
Baker, V.R., 2007. Greatest floods and largest rivers. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. John Wiley & Sons, Chichester, pp. 66–74.
Baker, V.R., Benito, G., Rudoy, A.N., 1993. Paleohydrology of Late Pleistocene superflooding, Altay Mountains, Siberia. Science 259, 348–350.
Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., Gagnon, J.M., 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. Nature 400, 344–348.
Broecker, W.S., 2006. Was the younger Dryas triggered by a flood? Science 312, 1146–1148.
Enikeev, F.I., 2009. Pleistocenoviye oledeneniya vostochnogo Zabaikaliya i yugo-vostoka sredneiy Sibiri (Pleistocene glaciations in the East Transbaikalia and the Southeast of Middle Siberia). Geomorfologiya 40, 33–49. In Russian.

Grosswald, M.G., Rudoy, A.N., 1996. Quaternary glacier-dammed lakes in the mountains of Siberia. Polar Geography 20, 180–198.
Herget, J., 2005. Reconstruction of Pleistocene ice-dammed lake outburst floods in the Altai Mountains, Siberia. The Geological Society of America Special Paper 386.
Jakobsson, M., Björck, S., Alm, G., Andrén, T., Lindeberg, G., Svensson, N.O., 2007. Reconstructing the Younger Dryas ice dammed lake in the Baltic Basin: bathymetry, area and volume. Global and Planetary Change 57, 355–370.
Komatsu, G., Arzhannikov, S.G., Gillespie, A.R., Burke, R.M., Miyamoto, H., Baker, V.R., 2009. Quaternary paleolake formation and cataclysmic flooding along the upper Yenisei River. Geomorphology 104, 143–164.
Krinner, G., Mangerud, J., Jakobsson, M., Crucifix, M., Ritz, C., Svendsen, J.I., 2004. Enhanced ice sheet growth in Eurasia owing to adjacent ice-dammed lakes. Nature 427, 429–432.
Krivonogov, S.K., Takahara, H., 2003. In: Kamata, N. (Ed.), Late Pleistocence and Holocence Environmental Changes Recorded in the Terrestrial Sediments and Landforms of Eastern Siberia and North Mongolia: Proceedings of International Symposium of the Kanazawa University 21st-Century COE Program, Vol. 1, pp. 30–36.
Leverington, D.W., Mann, J.D., Teller, J.T., 2000. Changes in the bathymetry and volume of glacial lake Agassiz between 11,000 and 9300 ^{14}C yr B.P. Quaternary Research 54, 174–181.
Leverington, D.W., Mann, J.D., Teller, J.T., 2002. Changes in the bathymetry and volume of glacial lake Agassiz between 9200 and 7700 ^{14}C yr B.P. Quaternary Research 57, 244–252.
Mangerud, J., Astakhov, V., Jakobsson, M., Svendsen, J.I., 2001. Huge ice-age lakes in Russia. Journal of Quaternary Science 16, 773–777.
Mangerud, J., Jakobsson, M., Alexanderson, H., Astakhov, V., Clarke, G.K.C., Henriksen, M., Hjort, C., Krinner, G., Lunkka, J.P., Möller, P., Murray, A., Nikolskaya, O., Saarnisto, M., Svendsen, J.I., 2004. Ice-dammed lakes and rerouting of the drainage of northern Eurasia during the Last Glaciation. Quaternary Science Reviews 23, 1313–1332.
Margold, M., Jansson, K.N., 2011. Glacial geomorphology and glacial lakes of central Transbaikalia. Journal of Maps 2011, 18–30.
Montgomery, D.R., Hallet, H., Yuping, L., Finnegan, N., Anders, A., Gillespie, A., Greenberg, H.M., 2004. Evidence for Holocene megafloods down the Tsangpo River gorge, southeastern Tibet. Quaternary Research 62, 201–207.
O'Connor, J.E., Baker, V.R., 1992. Magnitudes and implications of peak discharges from glacial Lake Missoula. Geological Society of America Bulletin 104, 267–279.
R-ArcticNET v4.0, 2010. Available at http://www.R-ArcticNET.sr.unh.edu, accessed November 18, 2010.
Shahgedanova, M., Mikhailov, N., Larin, S., Bredikhin, A., 2002. The mountains of southern Siberia. In: Shahgedanova, M. (Ed.), The Physical Geography of Northern Eurasia. Oxford University Press, Oxford, pp. 314–349.
Spielhagen, R.F., Erlenkeuser, H., Siegert, C., 2005. History of freshwater runoff across the Laptev Sea (Arctic) during the last deglaciation. Global and Planetary Change 48, 187–207.
Tarasov, L., Peltier, W.R., 2005. Arctic freshwater forcing of the Younger Dryas cold reversal. Nature 435, 662–665.
Teller, J.T., Leverington, D.W., Mann, J.D., 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. Quaternary Science Reviews 21, 879–887.
The INTAS Project 99-1669 Team, 2002. Available at http://users.ugent.be/~mdbatist/intas/intas.htm, accessed November 12, 2010.
Upham, W., 1896. The Glacial Lake Agassiz. USGS monograph.
Waitt, R.B., 1985. Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula. Geological Society of America Bulletin 96, 1271–1286.
Wiedmer, M., Montgomery, D.R., Gillespie, A.R., Greenberg, H., 2010. Late Quaternary megafloods from Glacial Lake Atna, Southcentral Alaska, U.S.A. Quaternary Research 73, 413–424.