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Sediment Records Indicate Outburst Events of Gega Dammed Lake at Yarlung Tsangpo River in the Tibetan Plateau

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1 Introduction

Outburst floods from glacial-dammed lakes are the main source of megafloods on earth (Baker, 2013). Outburst floods not only cut deep gorges, but also heavily impacted prehistoric human society deeply because they were the main sources of the great floods described in many legends(Baker, 2009). Outburst floods have even caused global climate change by changing ocean circulation after flowing into the sea (Clarke et al., 2003). The Gega paleo-dammed lake is, located at the entrance of the Yarlung Tsangpo gorge, and is the only paleo-glacial dammed lake found in the eastern Tibetan Plateau. However, no detailed analyses of its outburst floods have been carried out (Liu et al., 2015; Montgomery et al., 2004). The sediments from outburst floods, such as gravel dunes and slack-water deposits, were stored in limited amounts because downstream of the dam often consisted of gorges. In addition to forming downstream deposits, outburst floods can also cause a sudden decline in the dammed lake’s water levels, or even cause the lake to dry up. The sediment from dammed lakes can therefore be used to reconstruct the outburst events (Liu et al., 2014), as has been done for the Missoula dammed lake (Hanson et al., 2012). In previous work, we studied the feasibility of using lacustrine sediment from the Gega paleo-lake to reconstruct outburst events (Liu et al., 2018; Liu et al., 2014). In the present study, we selected the 28.5 m Guoruo (GR) lacustrine section of the Gega paleo-dammed lake for detailed analysis. We carried out detailed multiple proxy analysis and investigated the sand layers that indicated three outburst events.

2 Sampling and Methods

The Gega paleo-dammed lake and its surrounding geological environment have been described in detail in our previous papers (Liu et al., 2015; Liu et al., 2014). In this study, we focused on the GR section. The GR section (29°34'3.34"N, 94°28'7.29"E, altitude: 2976 m) is in a 28.5-m thick lacustrine sedimentary platform. The GR profile is capped by 0.25 m of residual slope sediments, mainly gray siltstone, partly mudstone and three sand layers. The bottom of the section is unexposed (Fig. 1a). Previous work dated five quartz optically stimulated luminescence (OSL) ages and two organic AMS ^{14}C ages (Liu et al., 2015). In the present study, 114 samples were collected at 25-cm intervals. Then, magnetic susceptibilities, grain size, total organic carbon(TOC) and nitrogen content(TN) of these samples were determined using the methods of Liu et al. (2018).

3 Results

The grain sizes in the GR section vary greatly. The median grain size (Md) ranges from 3 to 210 μm, and displays three high-value intervals, which indicates three sand layers (Fig. 1f). Although the change in low frequency field magnetic susceptibility (χ_{lf}) was smaller than the Md change, there was an obvious wide range

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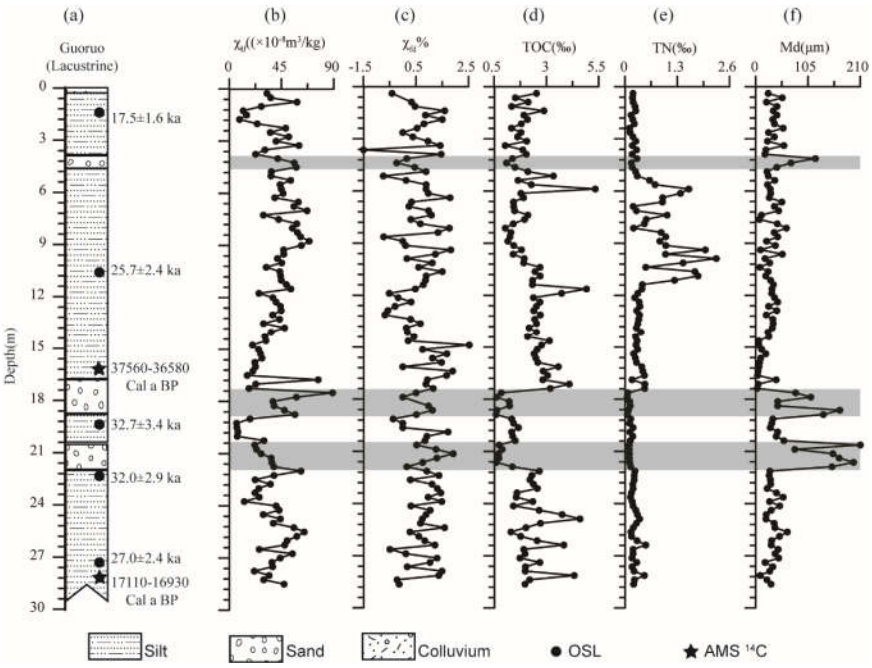

Fig. 1. Change characteristics for each index of Gruo section: (a) lithology and age, (b) magnetic susceptibility (χlf), (c) frequency-dependent magnetic susceptibility (χfd%), (d) total organic carbon (TOC), (e) total organic nitrogen (TN), (f) median grain size (Md).

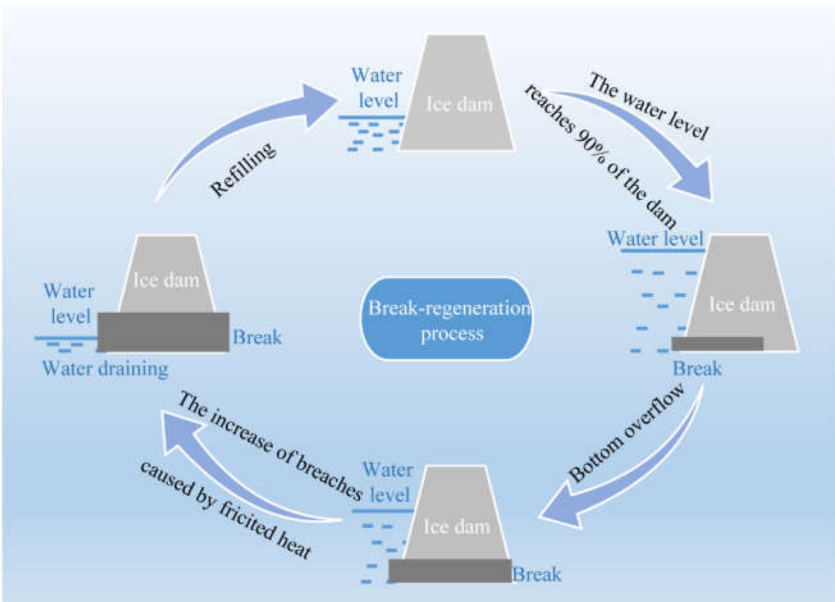

Fig. 2 Schematic map of the outburst-regeneration process for the glacial dammed lake.

from 6 to 89 × 10^{-8} m^3/kg. The sand layers corresponded with high χ_{lf} values (Fig. 1b). Frequency-dependent magnetic susceptibility (χfd%) was low (< 2.5%), which indicated that fine magnetic minerals were present insignificant amounts (Fig. 1c). In comparison with other lacustrine sediments, the TOC was very low (0.5-5.5‰) (Fig. 1d). TN ranged from 0 to 2.6‰; high values were found in the middle of the section, while the remainder of the section had low values that close to 0 (Fig. 1e).

Table 1 Mean values of the different proxies for three layers at 17.5-21.75 m in the GR section

Lithology	Md (um)	TOC（‰）	TN（‰）
17.5~18.75 m (sand layer)	97.5	0.859	0.0881
18.75~20 m (Silt layer)	39.8	1.45	0.153
20~21.75 m (Sand layer)	160.3	0.843	0.117

4 Discussion

4.1 Reviewing outburst events in the GR section

The results of grain size analysis show that there are three sand layers in the lake deposits of the GR profile. There are two main processes that may have created sand layers. First, the water level of the dammed lake decreased suddenly as a result of an outburst, and formed lakeshore deposits (Liu et al., 2014). Second, sudden flooding around the dammed lake carried sands to the lake (Liu et al., 2014). The χ_{lf} values of the three sand layers are higher than those of the neighbouring layers. This is consistent with agree with the high χ_{lf} values for sand layers in the Gega lacustrine sediment that we observed in our previous study (Liu et al., 2014). This indicates that the formation process of the sand layers in the GR section is consistent with the formation process of the sand layers of we previously studied. In the previous studies, the sand layers were mainly lakeshore deposits that did not involve long distance transportation, and therefore magnetic minerals were well preserved, resulting in higher χlf values in sand layers (Liu et al., 2014). Therefore, we suggested that the sand layers indicated outburst events. In addition, the χ_{fd}% of three sand sections were low, indicating that the magnetic minerals are coarse, thus providing further proof that the sand layers were well preserved and had not been subject to long distance transportation. Generally, the deposition rate of lacustrine sediment is closely related to grain size (Chen et al., 2004). As with loess, there is generally a positive correlation between deposition rate and grain size. Therefore, grain size can be used as an approximate indicator of sedimentation rate. The TOC and TN of the three sand layers were very low. This may have been caused by rapid deposition diluting organic matter content. The Md of two sand layers and one silt layer between 17.5 m and 21.75 m, and were used as a proxy for the sedimentation rate. The products of Md and TOC, and Md and TN were be used to reflect the deposition rate of organic matter. The results in Table 1 show that the deposition rates of organic matter in two of the sand layers were high. The original form of the organic matter usually remained unchanged, which indicated that the organic matter in the sand layers had undergone rapid burial. This provides further proof that these two sand layers had not experienced long distance transport.

In summary, the χ_{lf} and deposition rates of the organic matter of the sand layers indicated that the sand layers were lakeshore deposits. The three sand layers caused by sudden discharge from the lake, and indicate three outburst events. Although the OSL and ^{14}C ages did not clearly show the chronological sequence in the profile, all the OSL ages were 33-17 ka, and thus belong to the last glacial period (Fig. 1a). Therefore, we concluded that the GR section recorded three outburst events from the Gega lake.

4.2 Implications of the outburst events in the Gega dammed lake

Glacial dammed lakes are known to have been associated many outburst floods. For example, the Missoula glacial dammed lake in North America generated dozens floods (Hanson et al., 2012; Waitt, 1985). Although the mechanism of many outbursts of edice-dammed lakes is still being explored, it is commonly believed that when a glacier-dammed lake fills to near capacity, water begins to drain though subglacial tunnels (Walder and Costa, 1996). The GR section, formed 33-17 ka, recorded three outburst-regeneration processes, with one process lasting 5 kyr. The processes that occurred in the GR section can also be explained by the lake-filling/subglacial-tunnel mechanism. Because the density of the ice dam is less than that of water, when the lake surface of the glacial dammed lake rises to near dam height, the ice dam will float under the pressure of water. Then, subglacial tunnels will form at the bottom of the ice dam, and flowing water will promote the melting of the ice bottom and result in an outburst. After the outburst, the ice dam sinks again and is filled, and the dammed lake water is restored. This process forms an outburst-regeneration cycle (Fig.2). The volume of the Gega lake is approximately 170 km^3, and the average annual discharge at the nearest hydrometric station is150 km^3. Given this rate of discharge, it would be filled about 1.1 years. One possible reason for one process lasting long time was the existence of stable outlets; another possible reason was low water flows in the Yarlung Tsangpo River above the Tsangpo gorge during the last glacial period. The low flows occured because of a large reduction in precipitation and because most of the rain turning to ice.

Outburst floods can not only move the coarse gravel of the river bed, but also cause landslides on both sides of a river, which results in greater erosion than during normal river flows. Larsen and Montgomery (2012) suggested that the high erosion rate in the Tsangpo gorge was related to landslides induced by a massive outburst flood. Lang et al. (2013) calculated that the erosion of a paleo-flood with a flow rate of 10^6 m^3/s was equivalent to the erosion produced by normal flow over 1-4 kyr. The erosion caused by the Yigong outburst flood in 2000 was equivalent to 33 years of erosion by normal flow (Larsen and Montgomery, 2012). Erosion rate determined from low temperature thermal chronology ranged from a few mm to a dozen mm each year (Enkelmann et al., 2011; Finnegan et al., 2008). Periodic outburst floods from the Gega dammed lake may therefore be an important factor in the high erosion rates in this area.

5 Conclusion

Three sand layers were identified in the thick 28.5 m thick section of the GR profile, located at the Gega paleo-dammed lake. The χ_{lf} values of the three sand layers were high, the $\chi_{fd}\%$ was low, and the accumulation rate of TOC and TN were fast in three sand layers. This shows that the sand layers were proximal deposits and were buried rapidly, which indicates three outburst events. The Gega ice-dammed lake had experienced at least three outburst-regeneration events, and three outburst floods probably caused strong erosion of the Yarlung Tsangpo Gorge.

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References

Baker, V.R., 2009. *Overview of megaflooding: Earth and Mars, in: Burr, D.M.*, Carling, P.A., Baker, V.R. (Eds.), Megaflooding on Earth and Mars. Cambridge University Press, Cambridge, pp. 1-12.

Baker, V.R., 2013. *Global late Quaternary fluvial paleohydrology with special emphasis on paleofloods and megafloods*. Shroder, J.(Editor in Chief), Wohl, E.(Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA 9, 511-527.

Chen Jing'an, Wan Guojiang, Zhang, D.D., Zhang Feng, Huang Ronggui, 2004. Environmental records of lacustrine sediments in different time scales: Sediment grain size as an example. *Science in China Series D: Earth Sciences*, 47:954-960.

Clarke, G., Leverington, D., Teller, J., Dyke, A., 2003. Superlakes, Megafloods, and Abrupt Climate Change. *Science*, 301:922-923.

Enkelmann, E., Ehlers, T.A., Zeitler, P.K., Hallet, B., 2011. Denudation of the Namche Barwa antiform, eastern Himalaya. *Earth and Planetary Science Letters*, 307: 323-333.

Finnegan, N.J., Hallet, B., Montgomery, D.R., Zeitler, P.K., Stone, J.O., Anders, A.M., Liu, Y., 2008. Coupling of rock uplift and river incision in the Namche Barwa-Gyala Peri massif, Tibet. *GeoScienceWorld*, 120(1-2): 142-155.

Hanson, M.A., Lian, O.B., Clague, J.J., 2012. The sequence and timing of large late Pleistocene floods from glacial Lake Missoula. *Quaternary Sciednce Reviews*, 31:67-81.

Lang, K.A., Huntington, K.W., Montgomery, D.R., 2013. Erosion of the Tsangpo Gorge by megafloods, Eastern Himalaya. Geology 41, 1003-1006.

Larsen, I.J., Montgomery, D.R., 2012. Landslide erosion coupled to tectonics and river incision. *Nature Geoscience*, 5: 468-473.

Liu Weiming., Lai Zhongping, Hu Kaiheng, Ge Yonggang, Cui Peng, Zhang Xiaogang, Liu Feng, 2015. Age and extent of a giant glacial-dammed lake at Yarlung Tsangpo gorge in the Tibetan Plateau. *Geomorphology*, 246:370-376.

Liu Weiming, Zhou, G.G.D., Ge Yonggang, Huang Runqiu, 2018. Gradual late stage deepening of Gega ice-dammed lake, Tsangpo gorge, southeastern Tibet, indicated by preliminary sedimentary rock magnetic properties. *Acta Geophysica*, pp. 1-8.

Liu Weiming, Cui Peng, Lai Zhongping, Ge Yonggang, Hu Kaiheng, Zhang Wenjing, Su Chunjiang, Yi Zhiyu, 2014. Sediment rock magnetic properties indicate outburst events for Gega dammed lake at the Tsangpo Gorge in the Tibetan Plateau. *Chinese Journal of Geophysics*, 57: 2869-2877.

Montgomery, D.R., Hallet, B., 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.

Waitt, R.B., 1985. Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula. *GeoScienceWorld GSA Bulletin*, 96(10): 1271-1286.

Walder, J.S., Costa, J.E., 1996. Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. *Earth Surface Processes and Landforms*, 21: 701-723.