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Late Quaternary climatic control of Lake Baikal (Russia) turbidite systems: Implications for turbidite systems worldwide

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ABSTRACT

Lake Baikal (Russia) contains a variety of turbidite systems in different tectonic and depositional settings that provide tests for the role of Quaternary climatic change on turbidite system growth. During Pleistocene glacial climates, all types of systems exhibit increased sediment supply (high sedimentation rates, high net sand percent, thick sand turbidites) and progradation. During Holocene interglacial climate, all systems exhibit reduced sediment supply and retreat. Seismic profiles from the large Selenga Fan and small Tompuda Fan show (1) maximum fan growth during the late Pleistocene glacial melt time, where lobes and large channels reached the distal outer fan, and (2) fan retreat during the transition to the fully developed Holocene interglacial climate. For example, the Selenga Fan surface lobes backstepped ~55 km from the distal outer fan to the distal inner fan, and the large outer fan surface channel (~750 m wide, ~20 m levee relief) evolved to a smaller surface channel (~450 m wide, ~13 m levee relief) that extended only to the end of the inner fan. These results show that Quaternary climate controls the growth of the Lake Baikal turbidite systems in a setting where there are no significant water-level changes, which often are cited as the main control on turbidite system growth. The Lake Baikal and other marine turbidite systems suggest that climatic control of sediment supply, unrelated to sea-level lowering and tectonic effects, may have been a much more important control for turbidite systems than previously believed, not only during the Pleistocene, but perhaps also for ancient systems.

INTRODUCTION

Lake Baikal (Russia), the world´s oldest and deepest lake, formed in the rift zone between the Siberian platform and the fold belts of Mongolia, Asia (Fig. 1A) (Hutchinson et al., 1992). The lake is a unique natural laboratory for turbidite system research, because it contains a variety of depositional systems, such as sand-rich fans, mud-rich fans, and base-of-slope sand-rich aprons (Nelson et al., 1995, 1999; Colman et al., 2003). The tectonic setting is the primary control for these types of turbidite systems because it determines the size of drainage systems and the type of sediment supply they receive (Nelson et al., 1999). These systems include the small base-of-slope aprons developed on the northwest border fault margin with small drainages; the small sand-rich Tompuda Fan fed by a local glaciated valley river; and the large mud-rich Selenga Fan on the eastern ramp margin fed by the Selenga River, which has a large drainage area (Back and Strecker, 1998; Nelson et al., 2009).

During Pleistocene glacial time the growth rate of most turbidite systems in marine environments was greater than in interglacial time because of lower sea level and reduced base level of river drainages, increased sediment supply, and larger grain size (e.g., Nelson, 1976; Nelson and Nilsen, 1984). Most prevailing conceptual models attribute turbidite system growth to sea-level lowering, erosion related to river incision, and sediment delivery directly into canyon heads feeding the turbidite systems (e.g., Vail et al., 1977). Some recent models neglected to consider climate change, apart from eustasy, as a controlling factor for turbidite system growth (e.g., Brackenridge et al., 2011). Like most marine turbidite systems (e.g., Nelson and Nilsen, 1984), those in Lake Baikal exhibit, at ca. 13 ka (e.g., Carter and Colman, 1994), a transition from many thick sand turbidites in the late Pleistocene deposits to a few thin sand and silt lamina turbidites in a Holocene mud drape (Nelson et al., 1995). Average sedimentation rates (turbidites and mud interbeds) during the late Pleistocene (75 cm/k.y.) were ~3–4 times higher than those during the Holocene (20 cm/k.y.) in all basins of Lake Baikal (Nelson et al., 2009). The average net sand percentage changed from 21% in the late Pleistocene to 7% in the Holocene in all basins and was 5 times greater during the late Pleistocene in the North Basin, which was most affected by Pleistocene glaciation (Back and Strecker, 1998; Nelson et al., 2009).

Lake Baikal, however, did not undergo late Quaternary lake-level fluctuations sufficient to affect sediment supply because of base-level lowering. Colman (1998) stated that the climate-induced lake-level change was <~2 m during the late Quaternary, and Khlystov et al. (2008) estimated that lake levels were close to that of today, except for inferred short-term changes in the lake level (to 40–45 m) during the period 24–18 ka. Even if this latter questionable lake-level change occurred, sediment access continues at any lake level (Nelson et al., 1999). In addition, high sedimentation rates, high net sand percent, thick sand turbidites, and coarser grain size are found before and after the inferred 24–18 ka lake-level lowering, and extend to the end of the Pleistocene, ca. 13 ka (Nelson et al., 2009). Therefore, our hypothesis is that changes associated with glacial climates (e.g., vegetation changes, glacial meltwater fluxes) were the key factors controlling the Pleistocene growth of the Baikal turbidite systems.

Our study mainly focuses on the Selenga Fan in the Central Basin of Lake Baikal using high-resolution swath bathymetry and reflection seismic data (Fig. DR1 in the GSA Data Repository[1]) (Colman et al., 1996; De Batist et al., 2006). With these data we outline the evolution of turbidite channel and lobe distribution related to the increased growth of the Selenga Fan during Pleistocene glacial climates and the retreat of these features during the transition to Holocene climate (Fig. 1). The effects of climatic changes on the evolution of the Selenga Fan in the Central

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[1] GSA Data Repository item 2017048, Figure DR1 (seismic profile dataset and text figure locations), and Figure DR2 (channel morphologies), is available online at www.geosociety.org/pubs/ft2017.htm, or on request from editing@geosociety.org.

GEOLOGY Data Repository item 2017048 | doi:10.1130/G38163.1

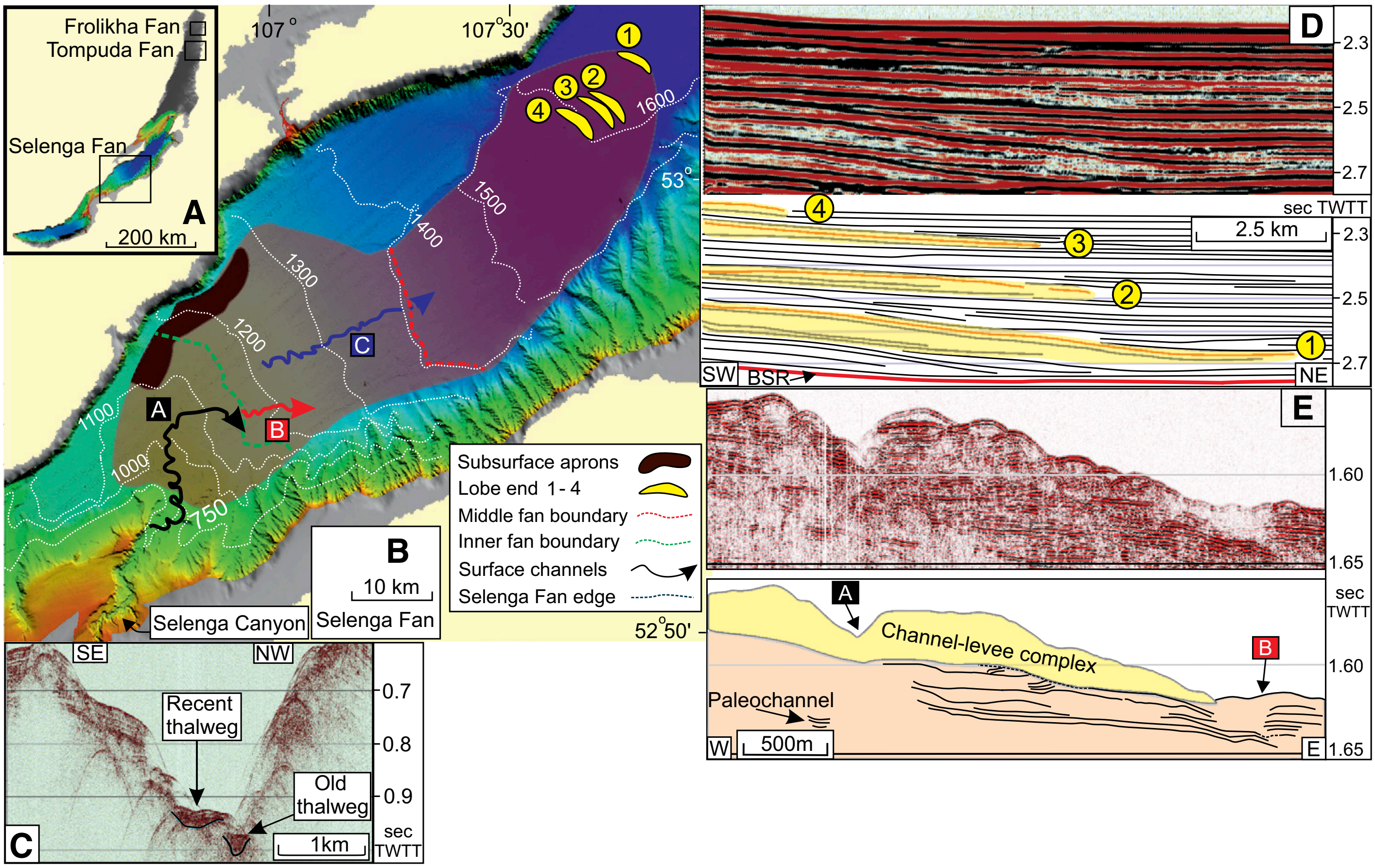

Figure 1. A: Location of the Selenga, Tompuda, and Frolikha Fans in Lake Baikal (Russia). B: Swath bathymetric map of the Selenga Fan (shaded area) with 100 m contour interval (De Batist et al., 2006), including the locations of canyons, channels, subsurface aprons, and depositional lobes. C: Seismic profile of the Selenga Canyon feeding the fan. D: Seismic profile interpretation showing oldest (1) to youngest (4) outer fan lobe backstepping. BSR—bottom-simulating reflection. E: Seismic profile interpretation showing younger channel levee complex A onlapping older larger channel B.

Basin are then compared to those on the Tompuda Fan in the North Basin (Nelson et al., 1995, 2009) and then to other marine turbidite systems such as the Rhône Fan and Ebro turbidite systems (Droz and Bellaiche, 1985; Nelson, 1990).

CHARACTERISTICS OF SELENGA CANYON, FAN CHANNELS, AND LOBES

The sediment transported by the Selenga River, which feeds the Selenga Canyon, is predominantly sourced from the large Siberian-Mongolian drainage basin and in part from nearby mountain areas, which were glaciated during Marine Isotopic Stage (MIS) 2 (Osipov and Khlystov, 2010). The Selenga Canyon extends northeast into the Central Basin from the Selenga River delta (Figs. 1A and 1B) and feeds the Selenga Fan through the most recent active Holocene channel A (Fig. 1B; Fig. DR2). The larger buried channel thalwegs of the canyon indicate that the canyon was more active in the past (Fig. 1C).

The Selenga Fan extends from a depth of ~900 m to 1600 m in the Central Basin, is as wide as 26 km, and as long as 80 km (Fig. 1B). The fan interfingers laterally with western border fault aprons, as well as short stream inputs from the eastern ramp margin (Fig. 1B). The fan is at least 300 m thick; however, aprons and the presence of a bottom-simulating reflection (BSR) related to gas hydrate–bearing sediment underlying the Selenga Fan make it difficult to estimate the exact thickness (Figs. 1B and 1D) (Vanneste et al., 2001).

A progressive decrease in the Selenga Fan growth pattern through time is shown by the morphology of the surface channel-levee complexes (C, B, and A in Fig. 1B). Only one distributary channel was connected with the Selenga Canyon and therefore active at any given time (Fig. 1B). The oldest and largest surface channel C (~750 m wide, ~20 m levee relief) is observed for 24 km on the surface of the middle and proximal outer fan (Fig. 1B; Fig. DR2). Its proximal part is buried under the younger channel-levee complexes A and B. At the inner fan to middle fan boundary, near the end of channel A, another segment of an older surface channel B is observed that has a width of 570 m and levee relief of 8–18 m (Fig. 1B; Fig. DR2). Channel B extends 11 km across the Selenga middle fan, where it decreases to 3–5 m of levee relief and 350 m width and then is buried (Fig. 1B; Fig. DR2). The proximal part of channel B is partially buried by the channel-levee complex of channel A. This confirms that channel B is older than channel A and that channel B is twice the size of the distal channel A at the same location (Figs. 1B and 1E). In the inner Selenga Fan, the youngest channel A has a surface expression for 24 km and terminates at the end of the inner fan (Fig. 1B). The proximal channel A is ~450 m wide, with levee heights of 12–13 m, but the width decreases at the end of inner fan to 200 m and levee heights decrease to 4–5 m (Fig. 1B; Fig. DR2).

The longest surface lobe (4) developed in the late Pleistocene (MIS 2) and ends 69 km from the Selenga Canyon mouth (Fig. 1B) (Nelson et al., 1995). Older subsurface lobes 1, 2, and 3 extend as much as 80 km from the canyon mouth (Figs. 1B and 1D). Any possible lobe at the end of channel A cannot be defined because of the overlapping lateral slope failures from the eastern ramp margin and the interfingering of a network of channel-levee complexes (Figs. 1B and 1E).

CLIMATIC CONTROL OF THE LAKE BAIKAL TURBIDITE SYSTEMS

Late Pleistocene glacial advance and retreat, plus development of tundra and/or steppe landscapes, increased the rates of erosion and sediment supply to the Baikal turbidite systems, and glacial meltwater dominated the sediment transport processes in the Baikal region (Shichi et al., 2009; Vologina and Sturm, 2009). All turbidite systems exhibit a decrease of sediment supply, channel size, and length of outer lobes during the transition to Holocene climate, when vegetation changed from tundra to birch and pine forests as glaciers receded (Figs. 1 and 2; Fig. DR2) (Shichi et al., 2009).

Central Basin

The Selenga Fan had its last maximum growth during the late Pleistocene MIS 2, as shown by the increased sedimentation rates and maximum extent of the surface lobe 4, 69 km from the canyon mouth (Figs. 1B and 1D) (Nelson et al., 1995, 2009). While climate ameliorated after the Last Glacial Maximum (ca. 20 ka) (Osipov and Khlystov, 2010), the outer fan surface lobe 4 retreated ~55 km to a position at the end of the youngest channel A as sediment supply decreased (e.g., 75% reduction in sediment rates) (Figs. 1B and 1D) (Nelson et al., 2009). The longer and older subsurface Selenga outer fan lobes 1–3 apparently developed during previous Pleistocene glacial climatic episodes. Except for surface lobe 4, there are no ages for the subsurface lobes, but the lobes repeat every ~120 ms (two-way traveltime) in the seismic data, or ~90–100 m (Fig. 1D). Assuming a typical average Pleistocene turbidite system sedimentation rate of ~100 cm/k.y. (Nelson and Nilsen, 1984), which is also observed in some Lake Baikal cores (Nelson et al., 2009), increased lobe growth (i.e., length) would occur every ~100 k.y. These growth stages appear to correlate with orbital eccentricity–driven glacial climatic cycles and increased sediment supply.

Like lobe backstepping, during the transition from MIS 2 to MIS 1 channel C, the largest surface channel on the Selenga Fan, retreated and became the smaller surface channel B (Fig. 1B; Fig. DR2). Channel B then shrank to the shortest, smallest, and youngest channel A (Figs. 1B and 1E). Similar to this pattern for the oldest surface channels, the largest and oldest subsurface channels also extended furthest out to the distal outer fan lobes (Fig. DR2). The change from a larger, older subsurface Selenga Canyon thalweg to the smaller surface thalweg parallels the channel changes on the fan surface that are related to the transition from Pleistocene to Holocene climate (Fig. 1C).

North Basin

In the North Basin of Lake Baikal, the small sand-rich Frolikha and Tompuda Fans, as well as the base-of-slope aprons, exhibit the same Pleistocene to Holocene depositional trends as the Selenga Fan (Fig. 1A). The maximum Pleistocene glacial extent and two recessional moraines have been dated at the Frolikha River mouth. At 40–35 ka (MIS 3) the glacier reached its maximum extent, 3–4 km offshore, and by 26–13 ka (MIS 2) the glacier had receded ~9 km inshore from its maximum extent (Back and Strecker, 1998). During the early Holocene, the glaciers in the valleys of both the Frolikha and Tompuda Rivers retreated and finally disappeared (Osipov and Khlystov, 2010). Like the Frolikha Fan, the Tompuda Fan growth was controlled by the North Basin glacial history (Back and Strecker, 1998; Osipov and Khlystov, 2010). The late Pleistocene turbidites of the Tompuda Fan and the base-of-slope aprons exhibit coarser grain sizes, numerous thick sand beds, and net sand content up to 8 times greater during the MIS 2 Pleistocene glacial climate compared to the mud drape with thin silt lamina of the Holocene (Nelson et al., 1995, 2009). Nelson et al. (2009) inferred that the oldest Tompuda Fan lobe reached its maximum extent from the youngest channel during the MIS 2 late Pleistocene glaciation of the Tompuda Valley; we now conclude that the progressive reduction of channel size and backstepping of lobes from 1 to 4 are linked to the regression of the Tompuda Valley glacier (Fig. 2).

IMPLICATIONS FOR MARINE TURBIDITE SYSTEMS

The sand-rich Tompuda Fan and base-of-slope aprons in the North Basin, as well as the mud-rich Selenga Fan in the Central Basin, are different types of turbidite systems, but they all exhibit the same depositional history related to climate change effects on vegetation and glaciation. These Baikal turbidite systems all show evidence of maximum size and growth rates and greater sediment supply during the late Pleistocene glacial climate (Figs. 1 and 2; Nelson et al., 1995). Other turbidite systems worldwide exhibit similar climatic-driven control on sediment supply and fan growth. The number of turbidite systems on the present seafloor doubled during the Pleistocene (Nelson and Nilsen, 1984); this emphasizes the importance of climate-related sediment supply. Like the Lake Baikal climatic control, most marine systems show thick turbidite deposition in the latest Pleistocene MIS 2 until the mainly hemipelagic deposition beginning in MIS 1 (ca. 13 to 12 ka), even while sea level was rising ~70 m (e.g., Nelson and Nilsen, 1984; Nelson et al., 1995).

When the Mediterranean Sea underwent significant sea-level lowering during Pleistocene glacial climates, the sediment supply of the Ebro turbidite systems from the Ebro River was an average of 15 × 10^6 t/yr, whereas during the Pliocene and Holocene times of high sea level and warmer climates it supplied an average of 5–6 × 10^6 t/yr (Nelson, 1990). Although the effects of climate and sea level are combined in these systems, pollen records show that during the Pleistocene glacial climates, the Pyrenean pine forests and Ebro Basin oak forests changed to grasslands. During the Holocene warm climate the forests returned, until humans deforested the Ebro drainage basin, similar to Pleistocene climate change, and the sediment supply reached 22 × 10^6 t/yr.

The Rhône Fan exhibits a reduced MIS 2 to MIS 1 sediment supply, because the youngest fan lobe (Neo fan), fed by the youngest Rhône Fan channel, ends on the inner fan (Droz and Bellaiche, 1985) just like the Selenga Fan channel A (Fig. 1B). This retreat of the Rhône Fan channel, similar to channel A, indicates the importance of Pleistocene to Holocene climate change on sediment supply and turbidite system growth.

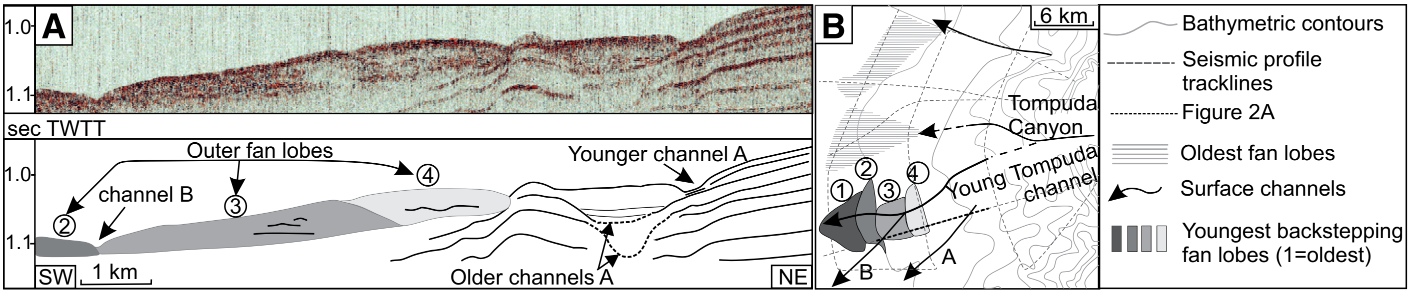

Figure 2. The Tompuda Fan (Russia). A: Airgun seismic profile showing lobe backstepping and change from older larger channels to younger, smaller channel A (dashed lines). B: Map view of backstepping from oldest (1) to youngest (4) outer fan lobes of Tompuda Fan. Dashed line in B shows profile A location. Modified from Nelson et al. (2009).

System growth is mainly unrelated to lower sea levels, because sea-level lowering contributes a <10% increase in sediment supply from river incision (Blum and Tornqvist, 2000). Although lower sea level results in more direct sediment access to marine turbidite systems, this low sediment input from river incision suggests that glacial climate change, causing increased sediment supply, is a significant controlling factor for Pleistocene lowstand fan growth.

CONCLUSIONS

This study emphasizes the importance of Pleistocene climatic control on sediment supply to deep-water turbidite system growth that is unrelated to lowered sea level. The depositional history of Lake Baikal turbidite systems shows that maximum sedimentation rates, net sand percent, turbidite bed thickness, channel size, and fan lobe extent occurred during the late Pleistocene glacial melt period. In contrast, smaller and shorter channels evolved and lobes backstepped as the warmer Holocene climate developed, glaciers disappeared, and forests grew. The importance of climatic control for the robust development of Pleistocene turbidites in Lake Baikal is shown, because with nearly constant lake level, the late Pleistocene to Holocene lithologic changes in Baikal are the same as marine turbidite systems with ~120 m of sea-level lowering. Marine turbidite systems also show the importance of climate as a key driver of turbidite system development, because of the doubled number of Pleistocene-age submarine fans on the present seafloor, significant turbidite deposition during rising MIS 2 sea level, and Pleistocene to Holocene reduction in sediment supply from rivers (e.g., the Ebro). The dominant glacial climatic control on Lake Baikal turbidite system growth suggests that climatic control on vegetation changes, glacial erosion, and glacial meltwater fluxes unrelated to sea-level changes may have been much more important than previously believed, not only in Pleistocene turbidite systems, but perhaps also for ancient turbidite systems.

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