Chapter 31
Late-Holocene Mass Movements in High Arctic East Lake, Melville Island (Western Canadian Arctic Archipelago)

Alexandre Normandeau, Gabriel Joyal, Patrick Lajeunesse, Pierre Francus, Scott Lamoureux, and François Lapointe

Abstract East Lake, located at Cape Bounty (Melville Island, Canadian High Arctic), was mapped using a high-resolution swath bathymetric sonar and a 12 kHz sub-bottom profiler, allowing for the first time the imaging of widespread occurrence of mass movement deposits (MMDs) in a Canadian High Arctic Lake. Mass movements occurred mostly on steep slopes away from deltaic sedimentation. The marine to lacustrine transition in the sediment favours the generation of mass movements where the underlying massive mud appears to act as a gliding surface for the overlying varved deposits. Based on acoustic stratigraphy, we have identified at least two distinct events that triggered failures in the lake during the last 2000 years. The synchronicity of multiple failures and their widespread distribution suggest a seismic origin that could be related to the nearby Gustaf-Lougheed Arch seismic zone. Further sedimentological investigations on the MMDs are however required to confirm their age and origin.

31.1 Introduction

Sediment archives from Arctic lakes are commonly used for paleoenvironmental and paleoclimatic reconstructions (e.g., Lapointe et al. 2012). Lake basins in the Arctic can accumulate large amounts of sediment derived from landscape runoff

A. Normandeau (✉) • G. Joyal • P. Lajeunesse
Centre d'études nordiques, GEOTOP and Département de Géographie, Université Laval, Québec, QC, Canada G1V 0A6

P. Francus • F. Lapointe
Institut national de la recherche scientifique, Centre Eau-Terre-Environnement, Québec, QC, Canada G1K 9A9

GEOTOP, City, Country

S. Lamoureux
Department of Geography, Queen's University, Kingston, ON, Canada K7L 3N6

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and in some cases preserve varves (e.g., Lapointe et al. 2012). Because this polar region is highly sensitive to climate change via feedback processes, high-resolution sedimentary records are particularly beneficial for assessing natural climate variability and for validating climate models (Kaufman 2009). However, an increasing number of studies demonstrate that lacustrine sedimentation is also influenced by mass movements, which can be unrelated to climate variability (e.g., Beck 2009; Waldmann et al. 2011). Understanding sedimentary processes within lakes is thus of major interest for interpreting past climate and predicting future climatic change. Studying such processes in Arctic lakes is challenging because they are often inaccessible with an ice cover for up to 10 months per year. Further, lake studies in the High Arctic rely solely on the interpretation of sediment cores while the geological, stratigraphic and geomorphological context in which sediment deposition takes place are often left undocumented.

In this paper, we report and describe for the first time sub-lacustrine landslides and sedimentary processes that occurred in a Canadian High Arctic Lake (East Lake, Cape Bounty) from the analysis of high-resolution swath bathymetry and sub-bottom profiling. This paper also aims at documenting pre-conditioning factors and the approximate timing of mass movement deposits in order to identify possible triggers for extreme events recorded in previously analyzed sedimentary records from the lake (Cuven et al. 2011; Lapointe et al. 2012).

31.2 Regional Setting

East Lake (unofficial name, 74° 53′ N, 109° 32′ W) is located on the south-central coast of Melville Island, in the western Canadian Arctic Archipelago (Fig. 31.1a). It is a small-sized and ~30-m deep lake (1 × 2 km) located 5 m above sea-level (asl; Fig. 31.1b). The area was entirely covered by the Laurentide Ice Sheet (LIS) during the Late-Wisconsinan (Nixon et al. 2013). By 14 ka cal BP, the retreat of the LIS margin led to the marine invasion, which reached areas today located at ~75 m asl. Following emergence from the sea due to glacio-isostatic rebound, an estuary and then a lake formed by 2195 BC and 243 AD respectively, providing a favorable environment for varve formation (Cuven et al. 2011).

The watershed of East Lake (and the adjacent West Lake) has been monitored since 2003 for hydrological, limnological and sediment transport and deposition studies, making it the longest comprehensive hydrological-limnological monitoring program in the Canadian High Arctic. E.g., Cuven et al. (2011) and Lapointe et al. (2012) have linked hydroclimatic variability to the physical and geochemical properties of the varves. Lapointe et al. (2012) documented a recent increase in rainfall events since 1920, with unprecedented levels occurring late in the twentieth century that are likely linked with the ongoing warming in the Arctic.

Cape Bounty is located ~150–200 km south-west from the Gustaf-Lougheed Arch Seismic Zone (GLASZ) (Fig. 31.1a). An earthquake swarm (65 locatable

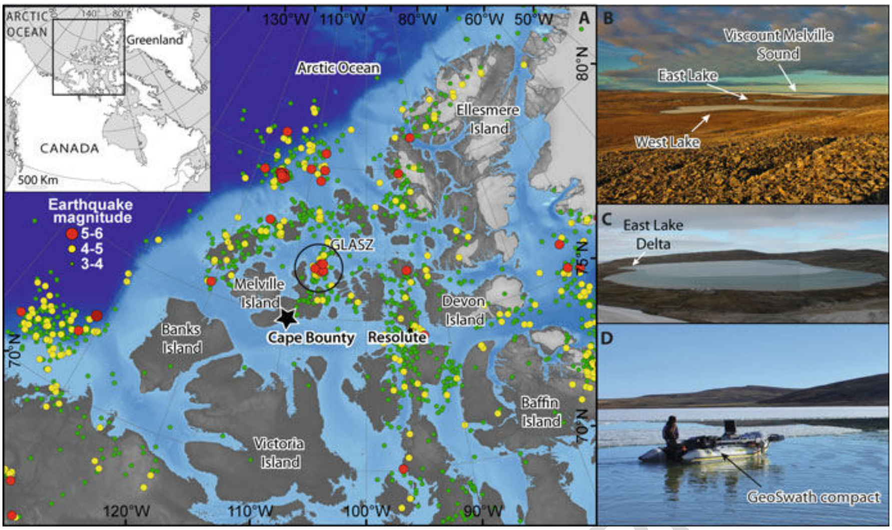

Fig. 31.1 (**a**) Location of Cape Bounty (Melville Island, Canadian High Arctic) and of recent earthquakes (GLASZ = Gustaf-Lougheed Arch Seismic Zone); (**b**) Overview of East and West Lake in early August 2013; (**c**) View of East Lake and its delta. Note the presence of ice, which limited the coverage of the hydroacoustic surveys over the entire lake; (**d**) GeoAcoustics GeoSwath echosounder mounted on an inflatable boat on East Lake

earthquakes in 55 days) with four major (M>5) earthquakes occurred in the region during November-December 1972 (Hasegawa 1977). An earthquake of M~5.6 also occurred in 2001.

31.3 Methods

A high-resolution bathymetric map of East Lake was produced from a hydroacoustic survey undertaken in 2013. A GeoAcoustics GeoSwath Plus compact interferometric bathymetric sonar (250 kHz) was deployed on a 2.5 m inflatable boat (Fig. 31.1d). A total of 12.5 km of subsurface data was acquired on the northern half of the lake using a 12 kHz Knudsen 3212 echosounder from the same boat and interpreted using The Kingdom Suite® and SonarWiz 5.0® softwares. Due to the presence of residual lake ice during the survey in early August 2013 (Figs. 31.1c, d), swath bathymetry data was collected over 75 % of the lake while sub-bottom profiles were collected only over the northern half of the lake area. The survey capabilities were highly dependent on daily wind directions which pushed the seasonal lake-ice cover from one end of the lake to the other.

31.4 Results

31.4.1 High-Resolution Bathymetry

East Lake forms a 30 m-deep overall round basin. The greatest depths are located in the central part of the lake, near the East River delta (Fig. 31.2). The slopes are steep on all sides of the basin, reaching ≥10° (Fig. 31.3a). The slopes are especially steep

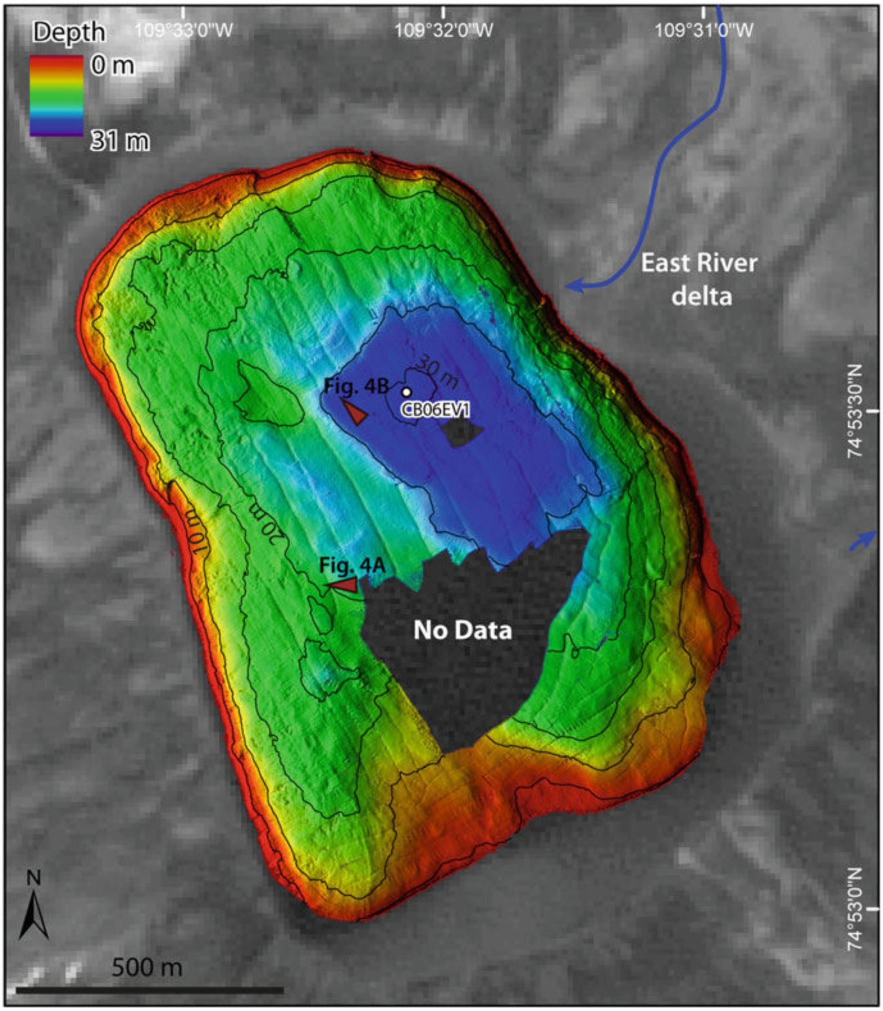

Fig. 31.2 Swath bathymetry map of East Lake (Cape Bounty, Melville Island). Regions of no data are due to the presence of ice during the 2013 survey. *Red arrows* indicate the viewpoints of Fig. 31.4

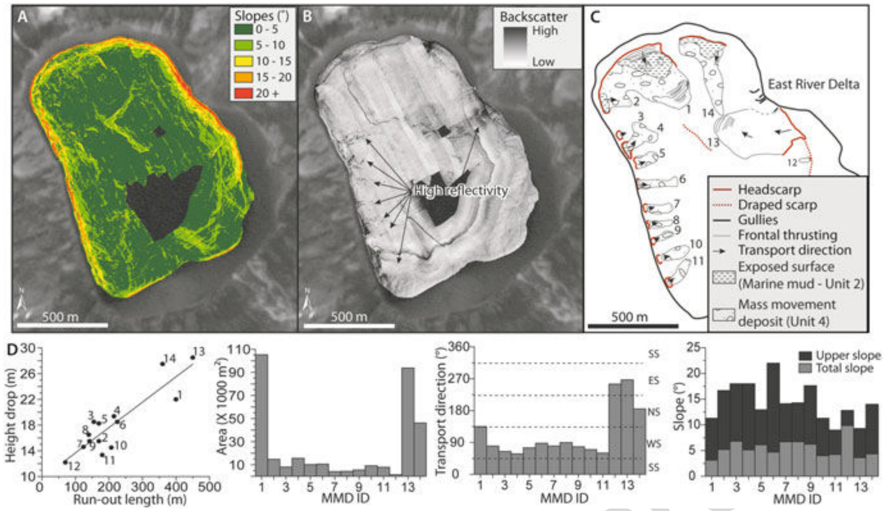

Fig. 31.3 Morphological characteristics of East Lake mass movements: (**a**) Slope map; (**b**) Reflectivity map; (**c**) Geomorphological map of mass movement's morphologies of the lake floor; (**d**) Morphological properties of 14 mass movements identified in (**c**)

on the eastern, northern and western margins of the lake, where they occasionally reach ≥15°. The southern portion has a gentle slope that rarely reaches ≥5°.

Two main types of lake-floor morphologies are observed in the lake: (1) gullies at the delta front; and (2) mass movement deposits (MMDs) throughout the lake, mostly on the northern and western slopes (Fig. 31.3c). Erosional gullies are ~50 m long and less than 10 m wide and are located at the mouth of the East River (Fig. 31.2). Fourteen MMDs were identified from surface morphology alone (Fig. 31.3c). The sizes of the MMDs vary along the slopes of the lake, but most have height drops of 14–20 m and run-out distances of 150–250 m. Three MMDs are much larger (No. 1, 13, 14; Fig. 31.3c), with run-out distances and height drops of >350 m and >22 m, respectively (Figs. 31.3c, d). The scar gradient of each MMD is generally ≥10°. The mean area of the deposits is 10,000 m^2, excluding the two largest that are ~100,000 m^2. One of the two largest MMDs is found near the delta front, and the other one on the northern slope. Compressional ridges are located at the front of these two larger MMDs while extensional ridges are observed near the headscarp of the northernmost MMD (Fig. 31.4b). The smaller MMDs consist mainly of boulder-size debris (Fig. 31.4a).

The backscatter map reveals a general low-intensity backscatter of the lake floor (Fig. 31.3b). This low intensity is interpreted to represent the undisturbed and normally deposited lacustrine sediment. The highest intensities observed along the western slope of the lake floor illustrate the debris nature of the MMDs (Figs. 31.3b and 31.4a). The lowest intensities are observed on the northern and southern parts of the lake, where mass movements cannot be identified from

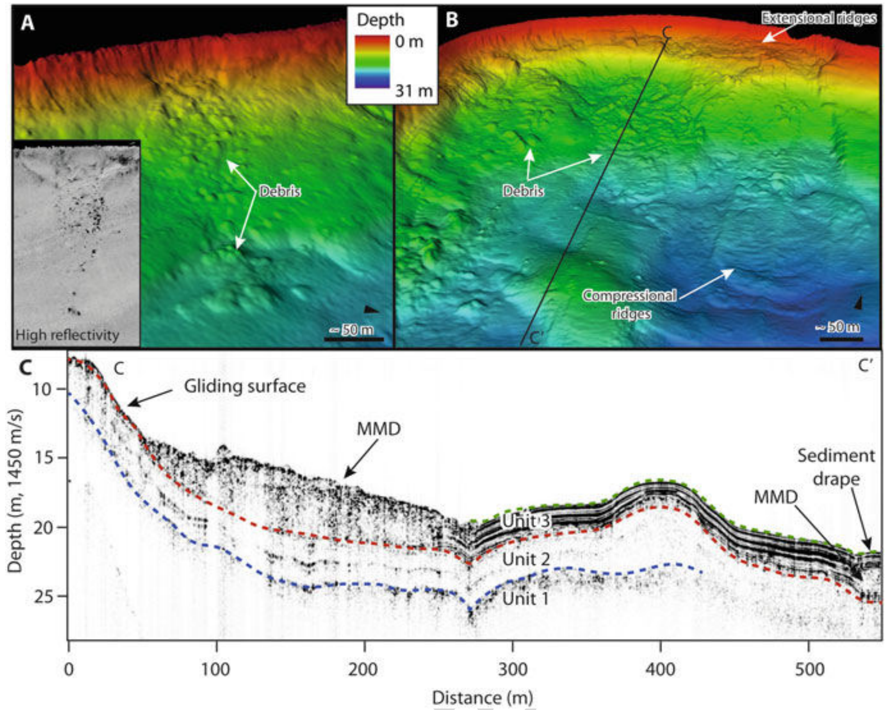

Fig. 31.4 3D view of mass movements 6 (**a**) and 1 (**b**) identified in East Lake. Location of images is provided in Fig. 31.2; (**c**) Sub-bottom profile illustrating the three acoustic units and MMDs. Location of profile provided in (**b**)

backscatter intensities. The delta front is also characterized by higher intensities, reflecting the coarser nature of the sediment discharged from the East River.

31.4.2 Acoustic Stratigraphy

Three acoustic stratigraphic units were identified in East Lake (Figs. 31.4c and 31.5). Lowermost Unit 1 is characterized by an absence of penetration and represents the acoustic basement. Unit 2 overlies Unit 1 and is acoustically transparent with few low-amplitude reflections. It appears to be present throughout the lake. Based on the depth of this unit from the lake bottom (≤4 m), its uppermost part appears to have been reached by a 7 m-long core (Cuven et al. 2011) and represents massive compacted mud, interpreted as marine sediments deposited prior to the lacustrine phase ≥4 ka BP. Unit 3 consists of high-amplitude reflections and drapes the underlying units. It was previously cored and consists of annually deposited silt and sand rythmites (varves) (Cuven et al. 2011; Lapointe et al. 2012).

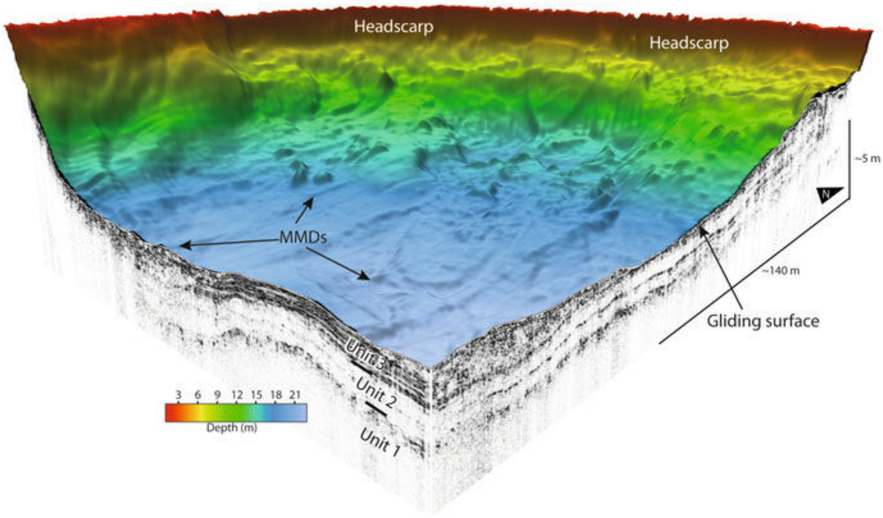

Fig. 31.5 3D view of swath bathymetry on sub-bottom profiles illustrating units 1–3 present in East Lake

Unit 3, however, is not present throughout the entire lake subsurface (Figs. 31.4c and 31.5). It is absent on steep sub-lacustrine slopes but can reach 4 m in thickness in the deepest part of the lake. At the top or within Unit 3, transparent to chaotic bodies (Fig. 31.4c) are interpreted as localized MMDs and are mostly observed at the base of steep slopes. The massive mud of Unit 2 is often exposed where the mass movements eroded the overlying Unit 3 (Figs. 31.4c and 31.5), illustrating that this unit probably acts as a gliding surface for MMDs.

31.5 Discussion

31.5.1 Factors Pre-conditioning Failures

High-resolution bathymetric data and sub-bottom profiles collected in East Lake show widespread evidence of MMDs. These MMDs are mostly located on steep slopes of the western and northern sectors of the lake. On the eastern side, steep slopes are also observed but gullies indicate that turbidity currents erode the lake floor, particularly at the delta front. Sub-bottom profiles reveal that the varved sediments (Unit 3) slid over the underlying massive mud (Unit 2), suggesting a stratigraphic control in the generation of MMDs where the top of Unit 2 acts as a gliding surface for the overlying silty-to-sandy laminated sediments. This abrupt change in type of sediment (e.g., marine to lacustrine) reduces slope stability and favours development of a weak layer or weak interface that subsequently can lead to failure (e.g., Strasser et al. 2007; Baeten et al. 2014). Therefore, the highly stratified varved sediments, the marine to lacustrine transition and the steepness of the slopes surrounding the lake are pre-conditioning factors favoring the triggering of mass movements in East Lake.

31.5.2 Recent Sediment Failures

The number of individual events responsible for the occurrence of MMDs in East Lake is difficult to quantify due to the absence of sediment cores associated with each mass movement. Based on the available sub-bottom profiles, at least two different episodes of sediment failures appear to have occurred during the last ~2000 years. ~1 m of varved sediment covers two MMDs, one of them visible on Fig. 31.4c. Moreover, core CB06EV1 (Fig. 31.2) has a prominent coarse layer at a depth of 1.3 m that was deposited at 1300 AD (Lapointe et al. 2012). This coarse layer (turbidite?) is probably the distal result of the lowermost MMD located on the eastern margin (MMD 13) thus suggesting a date of ~1300 AD for this first mass movement episode (Lapointe et al. 2012).

Core CB06EV1 recorded many coarse layers and turbidites, which suggests an influence from river floods in the accumulation of sediments in the lake (Lapointe et al. 2012). The presence of gullies reveals the occurrence of turbidity currents that could have been triggered by flood discharge and associated high suspended sediment loads. Hyperpycnal currents are frequent in freshwaters (e.g., Simonneau et al. 2013) and occur in East Lake since suspended sediment concentrations are especially high during snowmelt (Cockburn and Lamoureux 2008). Presently, the differentiation between river-generated turbidites (flood event layers) and mass movement induced turbidites has not been accomplished because previous studies in East Lake have not identified the distinct sedimentological signature of both deposits.

Thirteen other MMDs appear to have a similar and more recent age since they are located in the upper acoustic stratigraphy sequence (Fig. 31.4c). One of the largest turbidites analyzed in previous studies in the lake was dated with varves, ^{210}Pb and ^{137}Cs dating at 1972–1973 AD by Cuven et al. (2011) and at 1971 AD by Lapointe et al. (2012). This turbidite could be related to hyperpycnal flows but we rather interpret it as the distal result of a mass movement that reached the deeper basin (e.g., MMD 1 and/or 14). Based on this interpretation, the second mass movement event observed in the lake could have been triggered between 1971 and 1973.

The synchronicity of multiple MMDs and their widespread distribution in the lake suggest that mass movements were triggered by seismicity. An earthquake swarm occurred in the GLASZ during November-December 1972, the strongest event reaching M~5.7, at a focal depth of 9–14 km (Fig. 31.1a) (Hasegawa 1977). The distance of the earthquakes (200 km) would attenuate the intensity felt at East Lake. However, accepting Cuven et al. (2011) core chronology, the recent MMDs and the turbidite observed in core CB06EV1 could be related to seismic activity in the GLASZ since it is dated to the winter of 1972–1973. This hypothesis is also supported by the presence of the MMDs on the northern slope, far from the East River inflow where sediment loading would be minimal. Earthquake shaking causes significant strength reduction in stratified sediments (Cauchon-Voyer et al. 2008) and could have caused slipping over Unit 2 and the failure of the steep lake margins. However, more sediment cores are needed to constrain the chronology of MMDs in East Lake and infer their exact triggers through time.

31.6 Conclusion

Our survey in East Lake allowed for the first time the imaging of sediment instabilities in a Canadian High Arctic Lake. These results show that mass movements are ubiquitous in East Lake (Melville Island) and that their deposits cover a large part of the lake floor. Data suggest that steep slopes and the stratified package of lacustrine sediments on top of compacted marine deposits are favouring factors for the development of MMDs. Swath bathymetry and acoustic stratigraphy indicates that at least two different mass movement events occurred during the last 2000 years. A tentative timing for the events is proposed based on previous sediment core analysis (Cuven et al 2011; Lapointe et al. 2012) and acoustic stratigraphy. A first event appears to have occurred near ~1300 AD while more recent events are tentatively dated to 1970–1973 based on a prominent turbidite present in a core record. These recent MMDs could be related to an earthquake swarm that occurred in the GLASZ in the winter of 1972. Collection of cores from MMDs will lead to a better dating of the events and allow reconstructing Holocene paleo-seismicity or environmental change leading to sediment failures in this High Arctic Lake. Although the exact processes responsible for MMDs in East Lake are not adequately explained for the moment, we have demonstrated that the interpretation of sediment cores from high-latitude lacustrine environments for paleoenvironmental reconstructions needs to be supported by a high-resolution analysis of the geomorphology and stratigraphy of the lake floor.

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