Article

Giant Lake Geneva tsunami in AD 563

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To the Editor — Following the recent tsunamis in Indonesia (2004), Chile (2010) and Japan (2011), the risks associated with tsunamis have come into focus. Most tsunamis occur in the marine realm and are associated with large earthquakes. However, landlocked communities in regions without mega-earthquakes are not exempt from their destructive effects. Tsunamis have been recorded in lakes as a result of earthquakes and seismogenic landslides[1], rockfalls[2] and volcanic flank collapses[3,4], but have rarely affected large populations. Here we present a seismic survey of Lake Geneva along with sediment core analyses suggesting that, in AD 563, a large tsunami caused considerable destruction around the lake.

Today, the shores of Lake Geneva are inhabited by more than a million people. Of those, 200,000 live in the city of Geneva, an important financial centre and home to numerous international organizations. The Lake Geneva region is unlikely to ever experience a truly massive earthquake[5], nor is the topography near the city of Geneva steep enough to generate destructive wave-generating rockfalls. Yet, historical accounts[6,7] report a rockfall in AD 563 — the so-called Tauredunum event — in the mountains more than 70 km from Geneva, where the Rhone River enters the lake (Fig. 1 and Supplementary Fig. S1).

There are no reports suggesting that the Tauredunum rockfall was triggered by an earthquake[8], but we know that it destroyed several villages and caused a large number of casualties. Both historical accounts[6,7] describe how a tsunami, generated in Lake Geneva by the rockfall, inundated everything on the lake shore, devastated villages with their inhabitants and herds of animals, destroyed the Geneva bridge and mills, and entered the city of Geneva — passing over the city walls — and killed several people (Supplementary Fig. S2).

To investigate the event, we conducted a comprehensive offshore survey in the deepest part of Lake Geneva. Approximately 100 km of high-resolution seismic reflection profiles were obtained with a 3.5 kHz pinger source to image the sedimentation history of the lake. Furthermore, four 7–12 m long sediment cores were retrieved with a modified Kullenberg coring system for detailed sedimentological analysis, to correlate seismic units with the sediment facies and to retrieve organic samples. The organic samples were subsequently dated using accelerator mass spectrometry (AMS) ^{14}C dating.

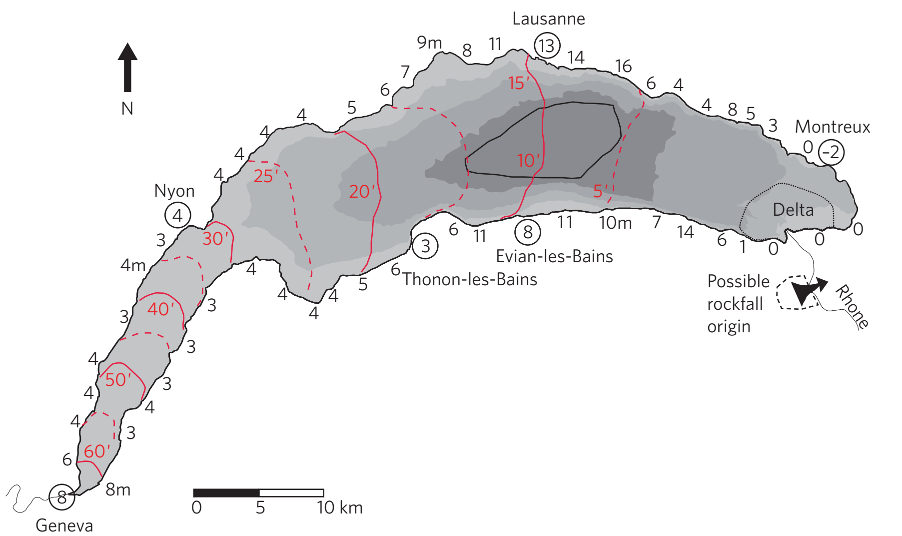

Figure 1 | Simulated tsunami wave height and propagation within Lake Geneva. In AD 563, a tsunami was triggered by a catastrophic mass movement of sediment, following a rockfall in the eastern part of the lake in the sublacustrine Rhone delta area (black dashed line). The amplitude of the first recorded wave varied along the shoreline (black numbers, in metres), as the wave propagated (red contours; red numbers indicate the time after the event in minutes). Water depth is indicated in grey shades (100 m intervals). The mass movement deposit (black contour) is located in the deepest part of the lake.

Analysis of the seismic profiles shows a giant sediment deposit beneath the lake bed that is characterized by chaotic and transparent seismic facies and an erosive base (Supplementary Fig. S3), which we interpret as a mass movement deposit. This lens-shaped deposit covers the entire deep lake basin, with a length of over 10 km and width of 5 km, an average thickness of 5 m and an estimated minimum volume of 0.25 km^3. The unit is thickest in the southeast, indicating an origin in the Rhone delta.

Analysis of the sediment cores shows that the mass movement deposit can be divided into two main units of roughly equal thickness (Supplementary Fig. S4). The lowermost cored unit comprises numerous small pieces of muddy sediments on the scale of centimetres, enclosed in a sandy matrix whose material becomes finer further up, and whose density decreases from 1.9 to 1.5 $g\ cm^{-3}$. The overlying sequence consists of a silty matrix, also finer towards the top, with a nearly constant density of 1.5 $g\ cm^{-3}$. Together, the longitudinal and vertical grading, the presence of mud pieces and the erosive base indicate that this mass movement deposit represents a turbidite, similar to a deposit observed in another perialpine lake that originated from a delta collapse[9].

We have estimated the age of the turbidite on the basis of three samples of organic material collected near its top (Supplementary Table). Two radiocarbon dates of leaf samples were used to build a linear relationship between sedimentation rate and time. We derive an interval of AD 381 to 612 with 95% probability (Supplementary Fig. S5). The third age, obtained from a wood sample embedded within the deposit, gives the earliest possible date for the event as AD 256 to 424 and thus validates the above age model. Since the AD 563 event is the only significant natural event recorded in historical accounts within our calculated age interval, we consider our dating results to be a strong indication that the deposit is linked to the AD 563 rockfall and tsunami.

The exact sequence of events linking the AD 563 rockfall and the Lake Geneva tsunami is uncertain. We propose that the impact of the rockfall on soft sediments near the lake shore destabilized the Rhone delta, similar to a smaller-scale event in Lake Lauerz, Switzerland[2]. We propose that part of the Rhone delta collapsed and evolved into a mixed turbidity current and debris flow, and that the resulting water displacement caused a tsunami wave on the lake surface. Our numerical simulations with a shallow water model[10] show that delta collapse in the lake generates a large tsunami at various locations along the shore, notably at Lausanne where a wave of 13 m is observed after only 15 minutes, and at Geneva where a wave of 8 m arrives 70 minutes after the mass movement is initiated (Fig. 1 and Supplementay Methods).

A reconstruction of the lake level and city configuration for the sixth century AD reveals that an 8 m wave would have passed over the city walls and hit the bridge and mills, as reported[6,7]. Today, a wave of this height would completely inundate large parts of the inner city of Geneva (Supplementary Fig. S6).

The event that triggered this tsunami was by no means unique. Our seismic reflection record indicates that large mass movements were generated several times during the Holocene epoch and could also have triggered destructive waves (Supplementary Fig. S3). Given that riverine sediment input is still loading the slopes of the Rhone delta, tsunamis may well occur in Lake Geneva in the future, whether they are triggered by rockfall, earthquakes or simply large storms resulting in slope failure. Such tsunamis, characterized by large wave amplitudes (3–13 m) and extremely short arrival times (less than 70 minutes), pose a direct and hitherto largely ignored threat to at least a million people living along the lake shores. Geneva is particularly vulnerable to such events, both because of its low elevation relative to the current lake level and its location at the tip of the funnel-shaped lake, a configuration that strongly amplifies wave amplitudes.

Our study highlights that not only cities located on sea coasts and fjords are at risk from destructive tsunamis, but so are densely populated lake shores. We believe that the risk associated with tsunamis in lakes is currently underestimated, and that these phenomena require greater attention if future catastrophes are to be avoided. ❑

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Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience.

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