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Supporting Information for

Shaking up assumptions: Earthquakes have rarely triggered Andean Glacier Lake Outburst Floods

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Introduction

This supporting information includes a note on the research consensus on the triggering of Glacier Lake Outburst Floods (GLOFS; Text S1). We provide a description of those lakes which were affected by the exceptional 1970 earthquake (Text S2 and Figure S1). Finally we provide a geological map for the region in which the six 1970 GLOFs occurred (Figure S2) and provide annotations on Google Earth images showing potential routes for mass movement triggering of GLOFs (Figures S3-S4).

Text S1: GLOF research consensus

The consensus of research efforts into Glacier Lake Outburst Flood (GLOF) hazards is that, for lakes dammed by moraines and bedrock, they are generated by the complex interaction of a series of (i) preconditioning factors (e.g. dam geometry and stability; location in the paths of mass movements), (ii) triggers (e.g. mass movements, earthquakes) and (iii) failure mechanisms (e.g. overtopping or breaching of the dam). The effect that earthquakes have in triggering GLOFs has, for the first time, been questioned in a recent community perspective paper (Emmer *et* al., 2022a); here they cite one instance from the Himalayas where a significant earthquake failed to initiate Glacial Lake Outburst Floods (Kargel *et al*., 2016).

Trigger parameters operate on short timeframes, such as seconds to days, whereas preconditioning parameters, operating from years to decades, set the conditions whereby a trigger might release a GLOF. Preconditioning factors relate to the individual characteristics of a given glacier lake (e.g. effective volume) and its impounding dam (e.g. type, width, height, and slope). In comparison, triggers vary depending on these preconditioning factors; e.g. for moraine dammed lakes, the most common GLOF triggers relate to mass movements sliding into glacier lakes (e.g. snow, debris, and or ice) which, upon impact, have the ability to generate waves that can result in failure mechanisms such as dam overtopping and/or failure. These myriad parameters have been reviewed and outlined by several studies (Richardson and Reynolds, 2000; Quincey *et al*., 2005; Emmer and Vilimek, 2013; Rounce *et al*., 2016; Kougkoulos *et al*., 2018; Racoviteanu *et al*., 2021; Emmer *et al*., 2022a) and the principal GLOF trigger mechanisms have become increasingly standardised.

Text S2: GLOFs associated with the 1970 earthquake

The 1970 Peruvian earthquake is associated with a total of six GLOFs (Table 1, Figure 1), all of which occurred on the eastern side of the Cordillera Blanca, Marañón river catchment (three GLOFs in the Librón valley, two GLOFs in the Cancará valley and one GLOF in the Safuna valley; see Figure 1). Post-event aerial images taken directly after the 31st May earthquake reveal that two GLOFs in the Librón valley originating from moraine-dammed lakes were triggered by large ice/ice-rock avalanches into these lakes, resulting in complete lake drainages (Figure S1D). These two lakes both reappeared later when ice deposited within the lake basins melted away. The third GLOF-producing lake in the Librón valley (bedrock-dammed lake Librón; Figure S1C) generated a GLOF due to dam overtopping as a result of the impact of the GLOF that occurred at the upstream Unnamed Lake. The two GLOFs in the Cancará valley originated from moraine-dammed lakes Cancará and Yanaraju (Figure S1A). As no in-lake deposition is visible in the post-event imagery (Figure S1B), it is likely that both of these GLOFs were triggered by a small-magnitude earthquake-induced ice avalanche/landslide sourced from the surrounding moraine slopes. The impact of these mass-movements resulted in dam overtopping and a ~4 m deep incision of the outflow channel in the outer slope of the Lake Cancará moraine dam.

In the Safuna valley, the 1970 earthquake is associated with the subsequent lowering of lake water levels at Safuna Alta by ~25-38 m (Lliboutry *et al*., 1977; Hubbard *et al*., 2005).

One explanation for this event is that it resulted from ground shaking-induced piping in the moraine dam (Lliboutry *et al*., 1977; Emmer *et al*., 2022b). Lliboutry *et al*. (1977) noted that muddy water was observed exiting the moraine within naturally occurring springs post-earthquake; the discharge of which increased exponentially over the following days. This release of potentially large volumes of water through the moraine, over a relatively short period of time, led this event to be subsequently classified as a low magnitude GLOF (Emmer, 2017). However, Hubbard *et al*. (2005) suggest that the drop in lake levels at Safuna Alta may have instead been the result of a seismically-induced increase in bulk permeability of the lake bed and moraine dam. This process may have reduced the amount of water being released downstream and/or abated any flood outburst event.

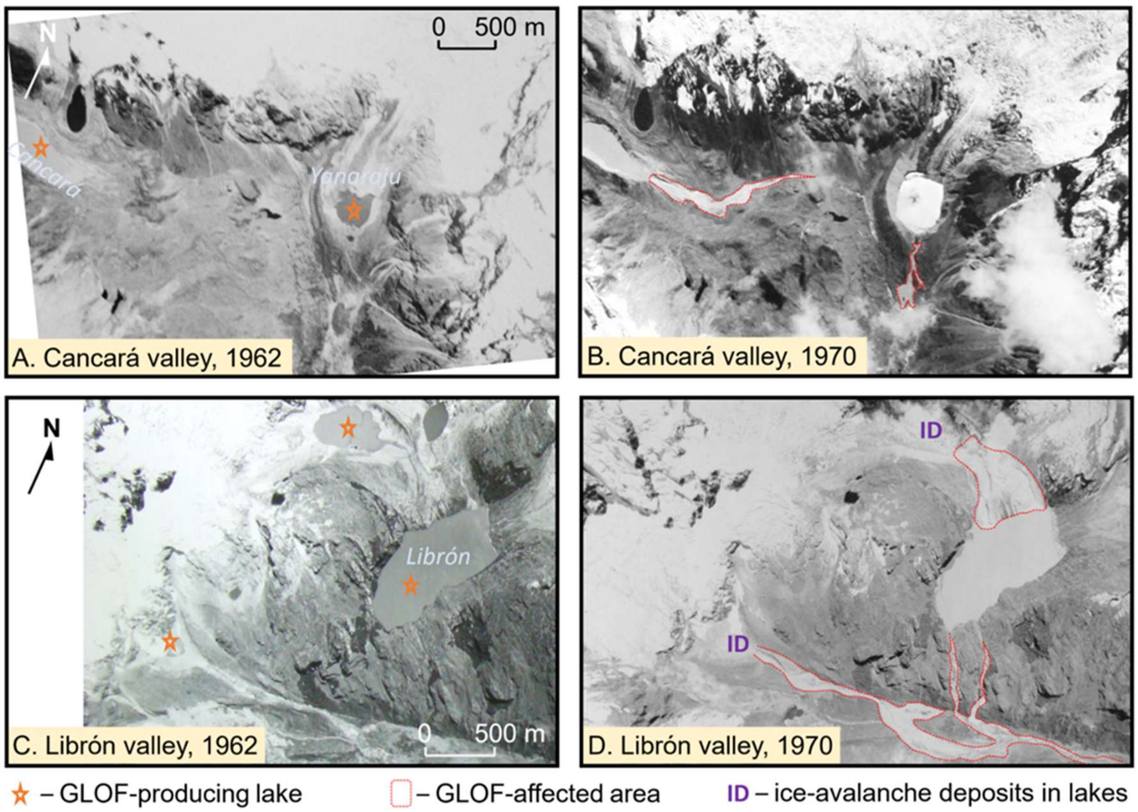

Figure S1. Upper parts of the Cancará and Librón valleys in the Cordillera Blanca, Perú, before (1962, A and C) and directly after the earthquake (1970; B and D). Geomorphic evidence for five earthquake-induced GLOFs are shown on post-event images. Aerial images: archive of the Autoridad Nacional del Agua (ANA), Huaráz, Perú (accessed in 2013 with the permission of Ing. Alejo Cochachin Rapre).

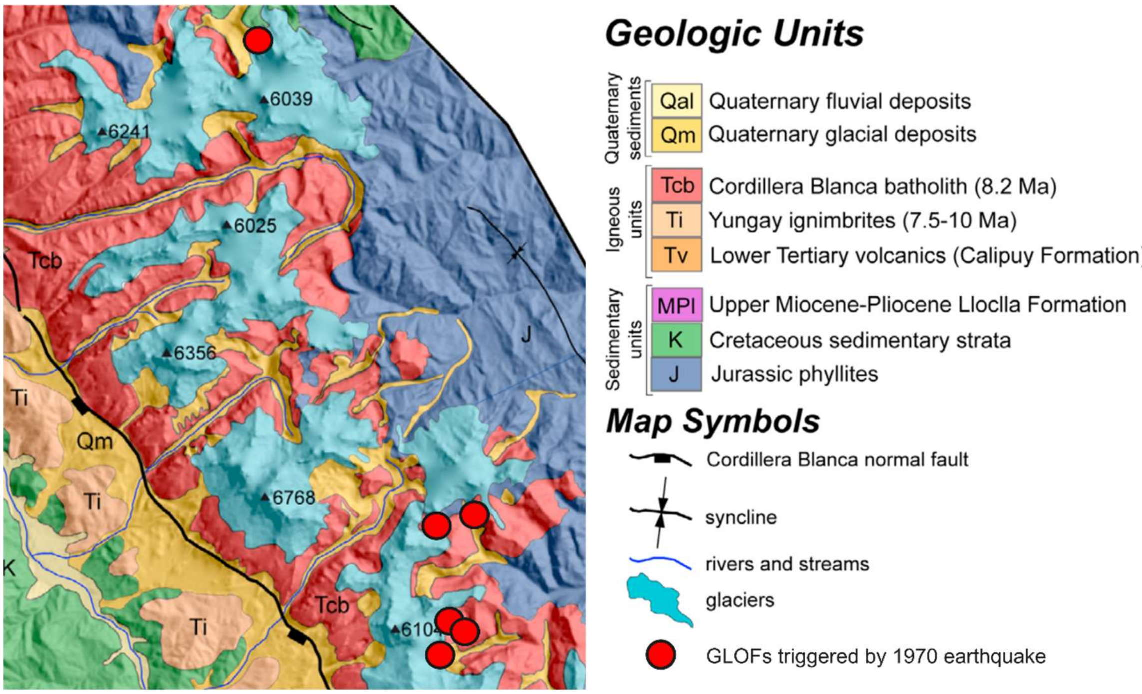

Figure S2. Location of lakes (red points) which emitted GLOFs due to the 1970 earthquake. The base is a geologic map compiled from other sources by Giovanni *et al.* (2010). These six lakes are close to the positions to which glaciers have recently retreated and where the batholith (unit Tcb, the red-toned map unit) contacts unit J. Jurassic phyllites (the blue-toned unit).

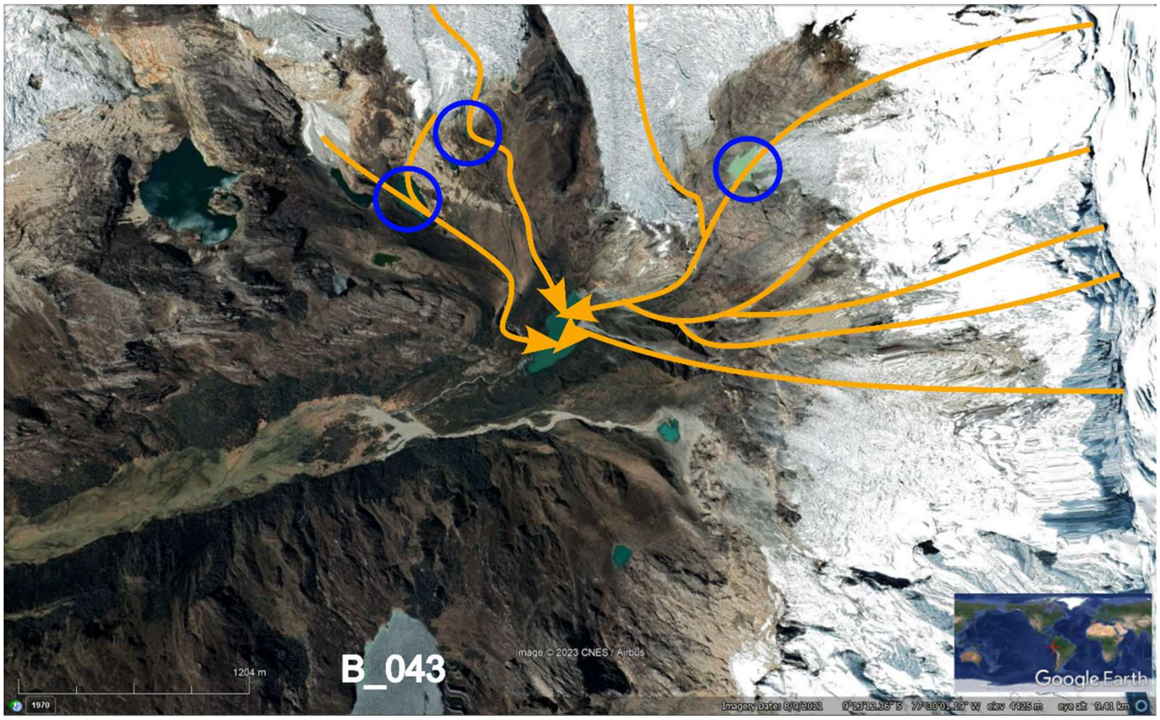

Figure S3. Annotations on a Google Earth scene showing illustrative lines of mass movements from surrounding peaks and slopes into a glacier lake. Some lakes are like this, with hazardous hanging glaciers, rock overhangs, and steep slopes on three sides, whereas other lakes have masses threatening to impact from fewer locations. Whether triggered seismically or some other way, the chances of mass movements triggering a GLOF are increased when the number of potential flow routes and mass movement sources are maximised. Evidence abounds here for recent mass movements into this lake and others. Blue circles indicate transitory lakes.

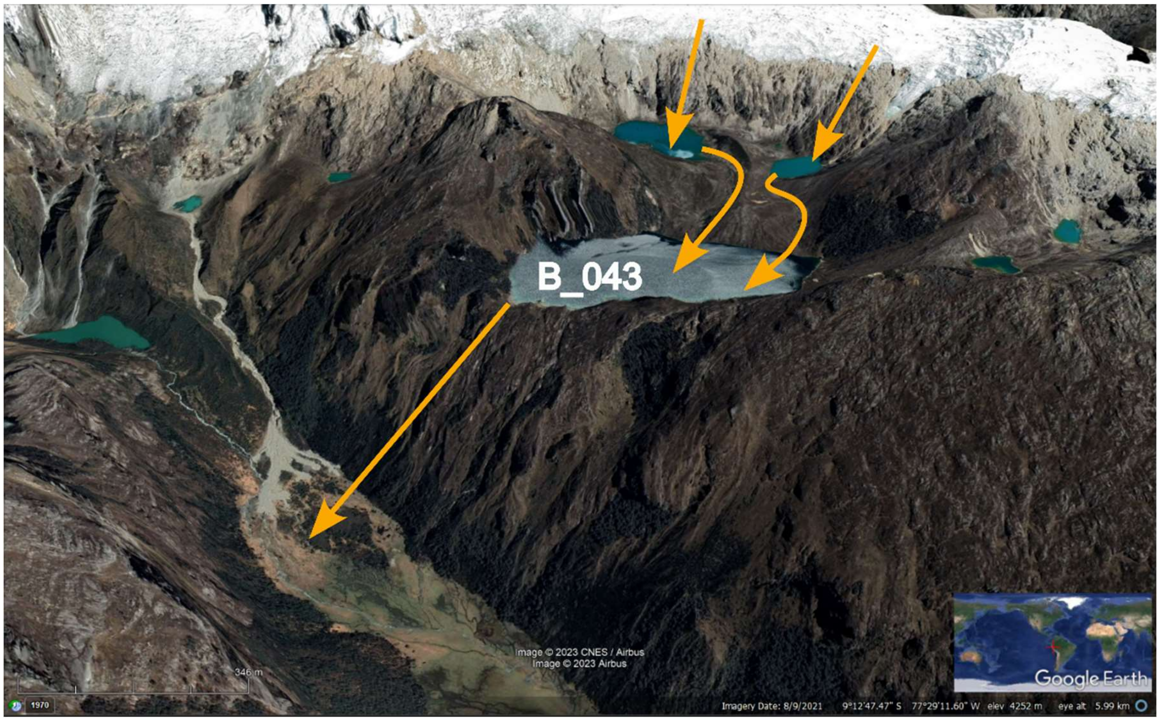

Figure S4. Annotations on a Google Earth scene showing illustrative lines of mass movements from surrounding peaks and slopes into glacier Laguna Librón. This lake is perched precariously above the valley below and has small lakes above it that could be involved in a chain reaction event, whether initiated be seismic activity or not, possibly triggering an outburst flood from Laguna Librón. Whether or not future seismicity unleashes another GLOF, or something else does, a GLOF from this lake seems likely at some point. This is true of many lakes in the Cordillera Blanca.