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

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**Key Points:**

- Glacier Lake Outburst Floods are a major risk concern, with earthquakes being commonly considered effective triggers in hazard assessments.
- Of 59 earthquakes (1900-2021) the effects of which intersect lakes in the Tropical Andes, only one triggered Glacier Lake Outburst Floods.
- We suggest that earthquake activity should be used as a secondary – not primary - susceptibility indicator for Glacier Lake Outburst Floods.

**Abstract**

As the world's glaciers recede in response to a warming atmosphere, a change in the magnitude and frequency of related hazards is expected. Among the most destructive hazards are Glacier Lake Outburst Floods (GLOFs), and their future evolution is concerning for local populations and sustainable development policy. Central to this is a better understanding of triggers. There is a long-standing assumption that earthquakes are a major GLOF trigger, and seismic activity is consistently included as a key hazard assessment criterion. Here, we provide the first empirical evidence that this assumption is largely incorrect. Focusing on the Tropical Andes, we show that, of 59 earthquakes (1900-2021) the effects of which intersect with known glacier lakes, only one has triggered GLOFs. We argue that, to help develop climate resilient protocols, the focus for future assessments should be on understanding other key GLOF drivers, such as thawing permafrost and underlying structural geology.

**Plain Language Summary**

Climate change is increasing glacier melt in high mountains and increasing the size and number of glacial lakes. Over time, these lakes may drain catastrophically to generate Glacier Lake Outburst Floods (GLOFs), which can devastate downstream communities and destroy valuable infrastructure such as roads, bridges, and hydroelectric power facilities. As a result, many risk assessments have been carried out to understand what the triggers of GLOFs might be, in order to better predict their occurrence. One of the main triggers has been assumed to be earthquakes, but this association has not been properly tested. In this paper, we use earthquake and GLOF data from the Peruvian and Bolivian Andes to test this and find that there is little association between earthquakes and GLOFs. We conclude by arguing that focus needs to be on other GLOF triggers, and earthquake activity should be used as a secondary – not primary – indicator in GLOF susceptibility studies.

## 1 Introduction

Climate change and recent glacier recession has been accompanied by an increasing concern about the nature, effects and future evolution of high-magnitude, low-frequency geological events in mountain glacial systems and their impacts on down-valley areas. These events include glacier lake outburst floods (GLOFs) and catastrophic rock and debris avalanches. It has often been assumed that climate change and geohazard events are necessarily linked, and our physical process understanding intuitively supports this assertion. However, attribution of such events to climate forcing has proven difficult, partly because the long-term datasets to test these relationships have often been lacking. This has certainly been the case for understanding the long-term context, and hence climate change attribution, of GLOFs (Harrison et al., 2018; Veh et al., 2019; Stuart-Smith et al., 2021). As a result, there is a pressing need for robust historical data on GLOF event magnitude, frequency, and triggers if we are to better understand the response of glacial environments to current and future climate change.

GLOFs are among the largest and most destructive natural hazards in glacierised high-mountain regions. They involve the rapid release of impounded meltwater from lakes that formed as mountain glaciers have receded and thinned in response to climate change. It has been assumed that GLOFs will become more frequent and more damaging, due to changing exposure, as climate change progresses; although this idea has recently been challenged (Harrison et al., 2018; Veh et al., 2019; 2022). The precise drivers of GLOF events have become the focus of considerable scientific enquiry. One central, long-standing assumption is that earthquakes are a major GLOF trigger (Plafker et al., 1971; Kargel et al., 2016) because they are thought to initiate dam destabilisation and/or failure, or because they generate landslides, rock falls and ice avalanches into glacier lakes, which then produce displacement waves, resulting in overtopping of, and incision through glacier-lake dams (Clague and Evans, 2000; O'Connor et al., 2001; Emmer and Cochachin, 2013; Westoby et al., 2014; Allen et al., 2017; Emmer et al., 2020; Supporting Information Text S1). Although a compelling theory, this assumption has only recently been questioned (Emmer et al., 2022a), but has not been empirically tested, until now.

A robust test of the earthquake trigger hypothesis is important because many GLOF hazard assessments include earthquakes or seismicity as a key glacier lake hazard ranking criterion (Zapata, 2002; Ives et al., 2010; Mergili and Schneider, 2011; Ashraf et al., 2012; Emmer and Vilímek, 2014; Emmer et al., 2016; Prakash and Nagarajan, 2017; Kougkoulos et al., 2018; Mohanty and Sabyasachi, 2021), which in turn has important implications for hazard and risk management decisions, and for sustainable development in mountain regions. Other similar GLOF studies acknowledge the importance of earthquakes but exclude them from their hazard assessments due to the difficulties involved in their prediction, or because their study areas are considered to be seismically homogenous (Emmer and Vilímek, 2014; Emmer et al., 2016; McKillop and Clague, 2007; Khadka et al., 2021).

The link between earthquakes and GLOF generation is largely intuitive as 1) mountain glacier lakes are often located in regions that are prone to seismic activity, 2) there is a strong link between earthquakes and the triggering of mass movements in mountains (Keefer, 2002; Kargel et al., 2016; Liu et al., 2020), and 3) moraine dams are thought to be inherently unstable, comprised of weakly consolidated and poorly sorted material, infrequently containing ice cores that degrade over time (Clague and Evans, 2000). However, the empirical evidence available to support such a relationship is both sparse and inconclusive (Allen et al., 2017). To date, earthquakes have only been implicated as a trigger in a total of 11 GLOF events globally (Table 1); seven are located in the Cordillera Blanca, of which six are associated with a single earthquake that occurred in 1970. Furthermore, there is currently no conclusive evidence of any GLOF having resulted from an earthquake-induced dam failure, with the majority of reported events thought to have been triggered indirectly through the initiation of mass movements (Table 1).

As is often the case with natural hazards in remote environments, knowledge regarding the trigger of observed GLOFs is generally limited, with available records being incomplete, of low resolution, and/or lacking in necessary detail (Carrivick and Tweed, 2016; Veh et al., 2019). Given the uncertainty concerning the role of earthquakes in the generation of GLOFs, it is important that this relationship is re-examined and properly tested. Here, we use a recent and comprehensive database of GLOF events (Emmer et al., 2022b) from the seismically active Peruvian and Bolivian Andes, and the USGS Earthquake Catalog (USGS, 2021), to test the relationship between these two physical processes.

**Table 1.** GLOF events reported to have been triggered by earthquakes.

| Date | Location | Trigger mechanism(s) | Source |
|---|---|---|---|
| **Switzerland** | | | |
| Approx. 13,760 B.P. | Lake Zurich, Limmat Valley | Lead hypothesis is that this event was triggered either directly or indirectly by a strong (> M6.5) earthquake that coincided with the GLOF. | Strasser et al., 2008 |
| **Nepal** | | | |
| Approx. 450 B.P. | Along the Seti Khola River, Pokhara Valley | High-magnitude GLOF event is thought to have been triggered by seismic activity. No evidence for this hypothesis is given. | Ives et al., 2010 |
| 1998 | Tam Pokhari, Khumbu region, Nepal | The GLOF triggering landslide was associated with a combination of excessive rainfall and anomalous seismic activity | Osti et al., 2011 |
| 2015 | Dudh Koshi basin, Khumbu region | GLOF generated from the glacier lake adjacent to Dig Tsho Glacier reported to have been triggered by an ice/rock avalanche initiated by the M7.8 Gorkha earthquake that occurred on $25^{th}$ April 2015. | Byers et al., 2017 |
| **Perú** | | | |
| 1725 | Rajururi Lake, Ancash Valley, Cordillera Blanca | Coincides with a major earthquake (reported in documentary sources). Likely triggered by mass movement. | Emmer, 2017 |
| 1970 | Lake Yanaraju, Cancará Valley, Cordillera Blanca | Mass-movement triggered by a M7.9 earthquake recorded on $31^{st}$ May 1970. | Emmer, 2017 |
| 1970 | Safuna Alta Lake, Cordillera Blanca | Lake lowering of ~25-38 m occurred following the 1970 earthquake. Lliboutry et al. (1977) suggest that this lowering was achieved via the gradual release of water through the moraine dam resulting from earthquake-induced piping. However, Hubbard et al. (2005) note that the lowering of lake water levels also could have resulted from a seismically induced increase in bulk permeability of the lake bed and moraine dam meaning any release of water downstream may have been limited. | Lliboutry et al., 1977; Hubbard, et al., 2005 |
| 1970 | Lake Cancará, Cancará Valley, Cordillera Blanca | Mass-movement triggered by the 1970 earthquake. | Emmer, 2017 |
| 1970 | Unnamed Lake[1], Librón Valley, Cordillera Blanca | Ice avalanche or glacier surge triggered by the 1970 earthquake. | Emmer, 2017 |
| 1970 | Lake Librón, Librón Valley, Cordillera Blanca | Mass-movement/GLOF entering the lake from Unnamed Lake[1] as a result of the 1970 earthquake. | Emmer, 2017 |
| 1970 | Unnamed Lake[2], Librón Valley, Cordillera Blanca | Mass-movement triggered by the 1970 earthquake. | Emmer, 2017 |

## 2 Materials and Methods

Earthquake data were downloaded from the USGS Earthquake Catalog (USGS, 2021) using the following search criteria: Earthquake magnitude: 4+; Start time: 1900-01-01 00:00:00; End time: 2021-05-17 00:00:00; Spatial extent: -61.172, 0.176; -82.661, -21.085; Event type: Earthquake; Search URL: https://tinyurl.com/Wood2023-USGS. A total of 11,733 earthquakes were identified and downloaded. We obtained a total of 160 GLOF-producing lake centroids for Perú and Bolivia (Emmer et al., 2022b), of which 86 GLOFs have been recorded since AD1900; the majority of these (n = 61) have known triggers, with "earthquake" cited on six occasions. The timing of 67 (post-1900) GLOFs are known to the exact year (Emmer et al., 2022b) and were used in the following analyses; the remaining 93 GLOFs were discounted in the analysis as we are unable to test for a temporal relationship when the date is unknown.

Keefer (2002) calculated the circular area of influence of earthquakes of differing magnitudes (>= M4) on landslide initiation:

$$log10A = M - (3.46 \pm 0.47) \qquad \text{[Eq. 1]}$$

Where $A$ is the area of influence (km$^2$) and $M$ is the earthquake magnitude.

As this relationship has not been explored for GLOF events previously, we selected the maximum critical distance as proposed by Keefer (2002):

$$log10A = M - (2.99) \qquad \text{[Eq. 2]}$$

We adapted this relationship by firstly calculating the area of influence of earthquakes, and then intersecting this with recorded GLOF events (Emmer et al., 2022b) spatially and temporally, across the Peruvian and Bolivian Cordilleras using R-Statistical Software. To achieve this, we converted both GLOF and earthquake centroids from decimal degrees (EPSG:4326) to a local Universal Transverse Mercator (UTM) coordinate system (UTM 18S or EPSG:5387; which covers 62% of the lakes in the region); we also calculated earthquake critical distance (Eq. 3) for the same earthquakes reprojected to both UTM 17S and UTM 19S, finding no difference in the calculated distances. We calculate earthquake critical distance ($E_{CritDist}$) in meters as:

$$E_{CritDist} = 1000\frac{\sqrt{10^{(M-2.99)}}}{\pi} \qquad \text{[Eq. 3]}$$

To quantify the spatial influence of earthquakes over GLOFs in the inventory we use the critical distance $E_{CritDist}$ (Eq. 3) to draw a circular buffer around each earthquake epicentre for each earthquake downloaded from the USGS Earthquake Catalog (USGS, 2021), these buffers were then intersected with the GLOF-producing lake centroids for Perú and Bolivia (Emmer et al., 2022b). For the temporal distribution, we selected four different time periods (this was to mitigate any potential lag effects in GLOF triggering and to unbias GLOFs that were not precisely dated: GLOFs that occurred on the same day, and GLOFs that occurred in the 30 days and 183 (six-months) days following an earthquake, the fourth time period, 366 days (one-year), was reserved for GLOFs which were only dated to the year. These time periods were selected arbitrarily as the authors found no literature relating to temporal lags in earthquake triggering of GLOFs. We intersected GLOF centroids, spatially and temporally, with all earthquakes downloaded from the USGS Earthquake Catalog (USGS, 2021).

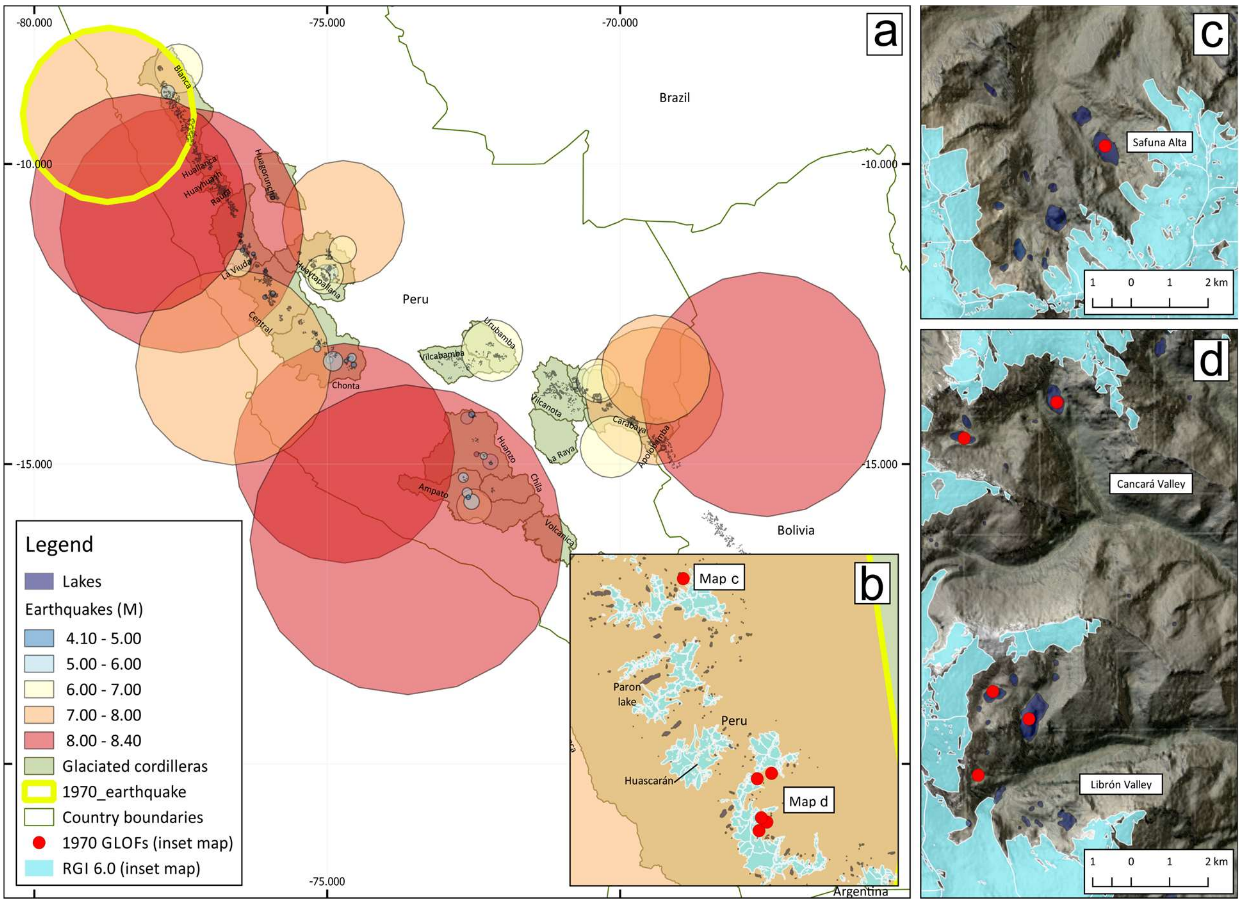


**Figure 1**. Locations of 59 earthquakes (USGS, 2021) that intersect with glacier lakes in the Peruvian and Bolivian Andes . (a) The 59 earthquakes (which occurred between 1900-2021) that intersect spatially with lakes in either the Bolivian (Cook et al., 2016) or Peruvian Cordilleras (Wood et al., 2021). Earthquake magnitude is shown by variation in colour, whilst the size represents the calculated critical distance ($E_{CritDist}$; Keefer, 2002; Eq. 3). The earthquake, outlined in yellow, is the 31-05-1970 M7.9 earthquake which resulted in six GLOFs in the Cordillera Blanca. (b) Overview of the Cordillera Blanca GLOFs (Emmer et al., 2022b) triggered by the 1970 earthquake. Also shown is the location of the Huascarán landslide, which is not implicated in the triggering of any of the six GLOFs, and the locations for maps (c) and (d). (c) Location of the GLOF-producing lake, Safuna Alta. (d) The Cancará Valley to the north, which experienced two GLOFs, and the Librón Valley, which recorded three GLOFs, associated with the 1970 earthquake.

## 3 Earthquake relationships to GLOFs

Of the 160 recorded GLOFs (Emmer et al., 2022b), 124 intersect spatially with any of the 11,733 earthquakes recorded in the USGS Earthquake Catalog (USGS, 2021) however, only one earthquake intersected the recorded GLOFs both spatially and temporally, and was identified as a trigger for six GLOFs - the M7.9 earthquake that occurred on 31-05-1970 (Fig. 1). Our analysis identified a total of six GLOFs, from six lakes in the Cordillera Blanca (Table 1; Figs. 1 and 2), which were triggered by this earthquake. The majority of these ($n = 5$) were from moraine-dammed lakes, with one recorded GLOF from a bedrock-dammed lake (Supporting Information Text S2). The fact that this analysis identified only those GLOFs that were already known to have been triggered by an earthquake, provides evidence that the defined earthquake-landslide relationship (Keefer, 2002) has merit more widely for the detection of earthquake-triggered GLOFs (where the trigger remains unknown) and potential for other earthquake-triggered hazards. Our analysis indicates that, for our region and time frame of study, seismic activity has been completely ineffective in triggering GLOFs, with the exception of one remarkable earthquake, which we now discuss.

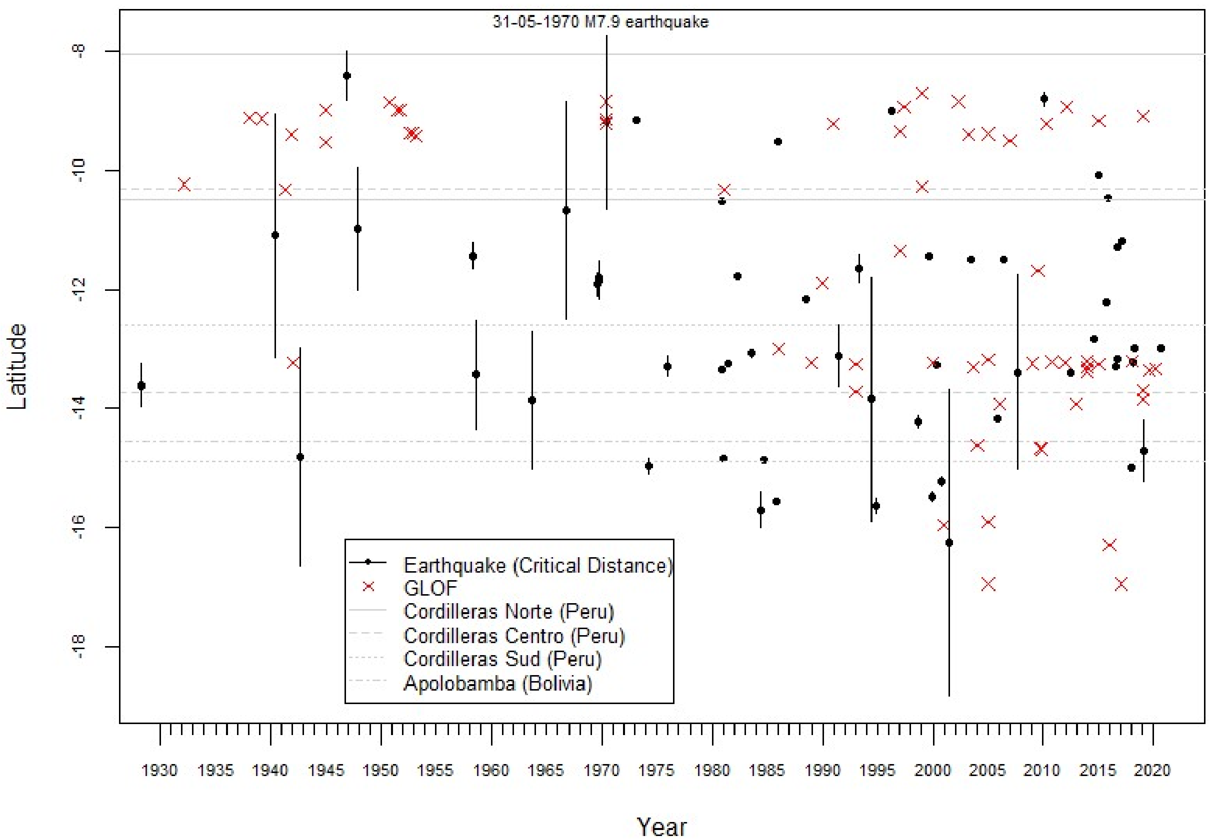


**Figure 2.** Earthquake timing and latitude (black dots), with critical distance thresholds (black lines representing the latitudinal distribution; Keefer, 2002; Eq. 3) for the 59 earthquakes (shown in Fig. 1) and timing for the 67 GLOFs in the comprehensive Peruvian and Bolivian inventory (Emmer et al., 2022b). The only earthquake that intersects known GLOFs spatially and temporally is the M7.9 earthquake which occurred on 1970-31-05 (indicated in the figure). Cordilleras Norte include Blanca, Huallanca, Huayhuash and Raura; Cordilleras Centro include La Viuda, Huaytapallana, Central and Chonta; Cordilleras Sud include Urubamba, Vilcanota, Carabaya and Apolobamba in Perú (see also Fig. 1). The seven southernmost GLOFs recorded in the inventory are recorded in Bolivian Cordilleras Apolobamba ($n = 2$), Real ($n = 3$) and Quimsa Cruz ($n = 2$).

1) Landslide-triggering of moraine overtopping waves: The fact that five of the six earthquake-associated GLOFs, all from one earthquake, were triggered by mass movements (Table 1) begs a question: why are there not more? After all, big earthquakes generate thousands of landslides (Keefer, 2002) and ice/rock avalanches (van der Woerd et al., 2004), some of which are large enough to produce large waves if they impact a lake. A possible reason is that glacier lakes tend

to be small, isolated, targets relative to the greater extent of river targets. Hence, river-blocking earthquake-triggered landslides and consequent dammed lakes and outburst floods may be more common than lake-impacting earthquake-triggered mass movements and consequent GLOFs (Fan et al., 2020). The triggering of GLOFs by mass movements may also relate to the stage of deglaciation, with changes to the number and size of lakes, mountain topography and the distance between glaciers and lakes playing an important role.

(2) Shaking disruption of moraines: Glacier lakes are embedded on valley floors, with the surrounding rugged terrain offering a modicum of protection against seismic disturbances. Seismic body waves (p-waves and s-waves) arriving obliquely toward the surface tend to attenuate near valley floors, where glacier lakes occur, helping to protect moraine dams against damage from seismic shaking. Seismic waveform modeling of the 2015 Nepal Gorkha earthquake (Dunham et al., 2022) and previous related work (Lee et al., 2009a; 2009b) has highlighted the role of seismic body-wave attenuation deep in valleys, and amplification on ridges and some valley walls. Surface waves, such as Love waves and Rayleigh waves (Kayal, 2008), are known to cause some of the most severe damage to construction and are likely responsible for initiating many landslides; however, they too would tend to be blocked by some types of rugged topography, particularly vertical cliffs, before waves can reach lake sites. In sum, shaking of moraine dams due to multiple wave modes may be suppressed. Furthermore, seismic shaking due to repeated earthquakes could cause settlement of moraine dams, increasing their stability by eliminating some porosity and permeability (Lliboutry et al., 1977).

(3) Sedimentology and water saturation: Liquefaction of moraines due to fluid overpressure (Staroszczyk, 2016), acoustic fluidization, or dispersive grain flow (Collins and Melosh, 2003) could be some key processes. However, sedimentology also may work against these processes. Liquefaction involves pore water expulsion from unconsolidated saturated sediment; and the latter two processes concern kinetic, quasi-elastic interactions of boulders and other particles, often in dry sediment flows. Several studies, summarised by the New York Department of Transportation (2015), consider the most liquefiable saturated sediment to be fine sands, coarse silts, and coarser beds up to gravel size, and specifically low-density fine sediments that contain a high void space; poorly sorted moraines are clearly not that. Seismic p-waves and s-waves are attenuated in water-saturated sediment (Kayal, 2008; Pride et al., 2004; Barriere et al., 2012; Holzer, 1996), which also may underlie and surround glacier lakes. Whether the disturbances causing this attenuation reduce the stability of moraine dams is unclear. Seismicity in some cases may improve moraine stability by way of settling and compaction, including possible closure of any meltwater thawed or eroded drainage ‘pipes.’ In any case, liquefaction of saturated moraine material may be less likely than often supposed. Acoustic fluidization of dry moraine material situated near to the angle of repose could produce boulder flows if fine grained material is absent; however, such portions of moraines are highly permeable and generally would not dam water that could burst out (being part of the freeboard). Moraines more often contain fines, which are easily crushed by motions of the coarse fractions, and pore water, both making particle collisions inelastic and making sudden collapse unlikely. Furthermore, these portions of moraines also generally have high shear strengths (Curry et al., 2009), making even steeply sloping moraines somewhat stable due to high internal friction stemming from the cohesion of the clay fraction, the interlocking of coarse boulders (including over-consolidation of some moraine material resulting in high cohesion), and the space filling sediment structure, which inhibits rotation and translation of clasts. Hu et al. (2021) concluded that seismic parameters are more important than soil parameters in controlling liquefaction, but they were considering a narrower range of sediment grading than prevails in

moraines. We think that both seismic parameters mentioned in point (2) and soil parameters are likely to work together to make moraines more stable than often supposed.

4) Fault scission: If active faults commonly cut through moraine dams, then we should expect more GLOFs from this trigger, yet we see no cases so far. Major faults often control deep erosion and valley development; however, glacier lake dams, where examined in field studies, do not have major faults cutting through them. For example, the 2015 Gorkha earthquake in Nepal involved a blind thrust (no surface rupture). Faults in close proximity to glaciers may have surface traces either higher (e.g. Chugach-Saint Elias Thrust in Alaska) or lower than lakes (e.g. the Chitina thrust in Alaska; Richter et al., 2006); in those situations, then no fault displacement cutting through the dams is possible. Most large earthquakes in Perú (Fig. 1) are associated with thrusting that surfaced at the Perú-Chile Trench. The Cordillera Blanca Normal Fault (Veloza et al., 2012) is located near many glacier lakes, and if it ruptured then GLOF triggering might occur. Although the Cordillera Blanca Fault is active, it has not ruptured since the start of the Spanish colonial era and may have ruptured just twice in the past 3000 years (Siame et al., 2006), so the chance of a further rupture during the period when glaciers still exist and before the lakes can infill with sediment, may be small. Finally, in some cases, direct scission may occur where fault displacement occurs beneath a moraine.

None of this implies that a future earthquake could not trigger a catastrophic GLOF, but the data clearly indicates that, in the region and timeframe of study, large earthquakes rarely ever trigger any GLOFs. This supports research focused on smaller regions, such as the case of the M7.8 2015 Gorkha earthquake in Nepal (Kargel et al., 2016) and more recent database for High Mountain Asia (Shrestha et al., 2023). A notorious exception is the 1970 Perú earthquake (Lliboutry et al., 1977; Zapata, 2002; Hubbard et al., 2005; Emmer, 2017; Emmer et al., 2020; 2022b), which we consider in the next section. Although five of the six GLOFs triggered by that earthquake were from moraine-dammed lakes (Supporting Information Text S2), there is scant or no evidence for direct destabilization of moraine dams either by shaking or by faultline scission of the moraine dam. Instead, seismically triggered lake-impacting mass movements caused moraine overtopping or failures in most cases (Byers et al., 2017; Emmer, 2017) (Supporting Information Fig. S1).

## 4 Why was the 1970 earthquake special?

The 1970 Perú earthquake (Fig. 1), is known to have generated thousands of mass movements, including rockfalls, rockslides, and soil slides (Keefer, 2002). That six GLOFs - in three different valleys (Fig. 1) - were triggered by this earthquake is remarkable, especially considering the global record shows that no other comparable event triggered multiple GLOFs.

Lithology is a well-known variable that affects landslide potentials. Since landslides are a major trigger of GLOFs, and were implicated in five of the six 1970 GLOFs, lithology is an important variable in affecting GLOF susceptibilities. Well bedded sedimentary rocks of distinctly contrasting lithologies, for instance, can be prone to form bedrock overhangs, wedge failures, gully erosion, and so on, which can yield landslides; whereas unweathered or superficially weathered granitoid rocks may tend to resist landsliding. Deeply weathered granites, however, with both frost wedging and hydrolysis alteration, can produce hoodoos and other potentially unstable topography, such that deeply weathered, long-ago deglaciated granitoids could yield landslides and trigger GLOFs. Lithology also influences moraine sedimentological factors, such as permeability, porosity, particle size distribution, and internal friction, which in turn influence the hydrogeological and structural factors that influence ice content, seepage, sapping, tunneling, slumping, buoyancy, and resistance to wave and flood current erosion. Hence, lithology of the basin in which a glacial lake exists must influence its stability and susceptibility to GLOFs, but ] is an important geotechnical matter that requires further study.

Putting this fundamental logical understanding into the specific context of a particular glacial lake is harder, as so many other factors can influence GLOF susceptibilities. We have examined the geological-lithological environment of the six 1970 GLOF-emitting lakes and that of nearby lakes that did not emit GLOFs during the 1970 earthquake (Fig. 3). We have only some inconclusive observations that warrant further investigation but do not give us a "smoking gun" explanation for why the 1970 earthquake produced a cluster of six GLOFs, whereas most other earthquakes produce no GLOFs at all.

The six 1970 GLOFs occurred near the contact of the Cordilleran Batholith—a granitoid intrusion—with Mesozoic sedimentary rocks (Fig. 3; Supporting Information Fig. S2). As an example, Fig. 3 shows lakes on the east-side of the Hualcán massif, some of which emitted GLOFs in 1970 (among them, Laguna Librón; B_043 in Emmer et al., 2022b). In contrast, none of the west-side lakes, which are completely situated within the batholith (lithologically, mainly granodiorite and tonalite - siliceous igneous intrusive rocks - which appear as massive or chaotically but massively structured light-toned rocks) emitted GLOFs during the 1970 earthquake. On the east-side, the lakes are very near the contact between the batholith and dark-toned Mesozoic sedimentary and meta-sedimentary rocks, such as phyllite, which in places are clearly bedded and elsewhere are more massive. For the most part, the east-side lakes are situated within the dark-toned sedimentary/metasedimentary rocks and are either dammed by dark-toned bedrock or by moraines that include eroded debris from dark-toned rocks. On the west-side, the dams are either light-toned batholith rocks, or debris that was predominantly eroded from the batholith. Hence, the dam characteristics differ, and the bedrock immediately adjacent to the lakes also differs between east- and west-side lakes.

This relationship could look like a "smoking gun" explanation for the cluster of 1970 GLOFs, but the situation is more complex. Firstly, Laguna 513 did not emit a 1970 GLOF, but it did emit one in 2010. Secondly (as shown in Supporting Information Fig. S3 and S4), some lakes are surrounded by steep relief, with rugged peaks, overhangs, and hanging glaciers, and some have smaller perched lakes along the flow routes for mass wasting materials. Such lakes have many chances to be hit by large mass movements, whether seismically induced or not. Some other lakes have comparatively fewer places surrounding them where a mass movement can drop directly into the lake. These are all important details, and the topographic setting may well be more important than lithology, although topography could be reflective of lithology due to differential glacial erosion rates.

The broad implications of our research findings, suggesting that seismicity only rarely initiates GLOFs, should be carefully considered. It is important, moving forwards, to understand what made the 1970 earthquake, and the lakes which experienced GLOFs, exceptional: what are the characteristics of the moraine dams that failed, and do those characteristics differ from those of glacial lakes that did not fail both from the 1970 earthquake and the 58 other earthquakes? What seismic moment, seismic source parameters, wave characteristics, and ground dynamic motions are required to cause these dams to fail? How have changes in lake size distribution affected the probability of earthquakes triggering GLOFs across the region? It is important to acknowledge the potential for various triggering events, including seismic activity, to contribute to the occurrence of GLOFs. We offer this point as a caveat to our work's overall conclusions, which appear to be rather robust on the whole.

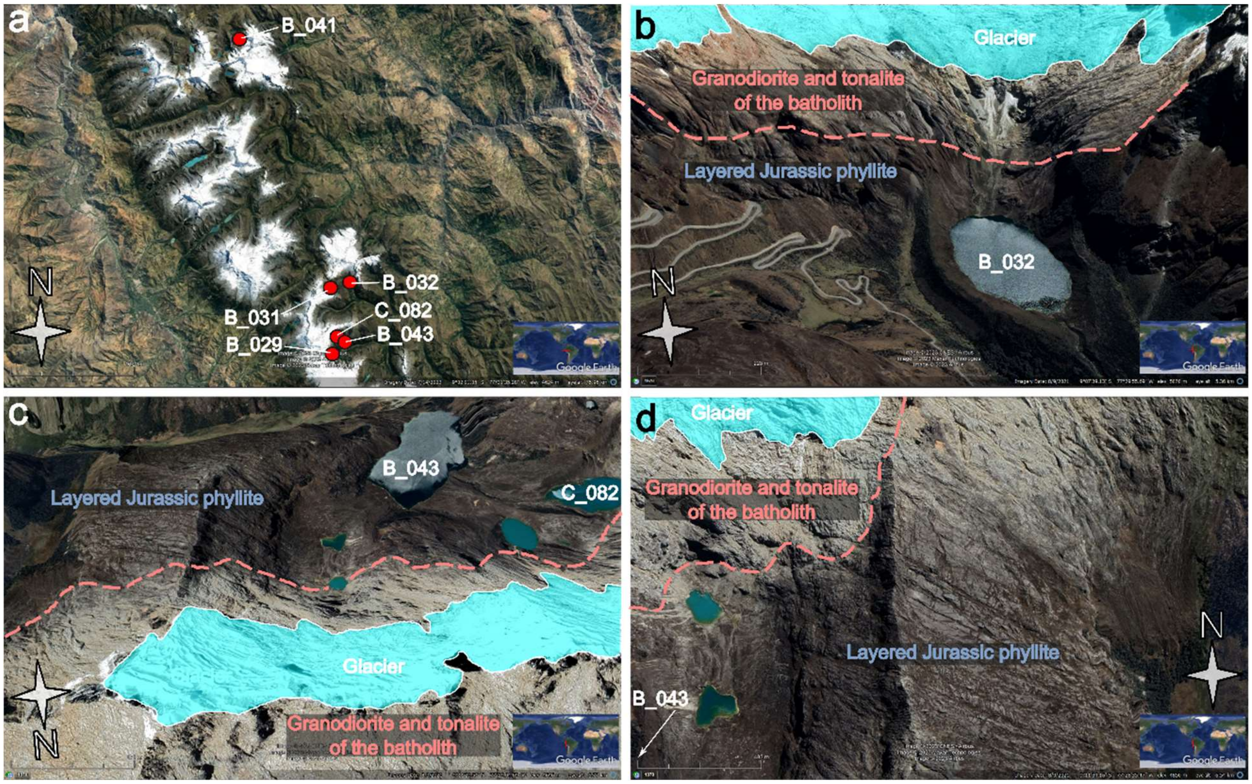


**Figure 3.** Perspective views (Google Earth) of the Hualcán massif area (lakes are labelled using identifiers from Emmer et al., 2022b). a) Locations of the lakes which experienced a GLOF as a result of the 1970 earthquake (see also Fig. 1b for reference). b-d) GLOF lakes are labelled, and views showing the geologic contact between the batholith and the phyllite (sketched as a dashed line), which are not sharp in this area (but are in nearby locations).

A notable aspect of the 1970 earthquake is that it had a comparatively deep hypocenter and movement on a normal fault (Abe, 1972; Beck and Ruff, 1989), rather than the low angle thrust faults on which movement causes most large, destructive earthquakes. We do not know how this source parameter may be linked to GLOF triggering. It is known that fault geometry and slip are responsible for producing the broad wavefield of earthquakes, and the details of the wave fields affect the propagation and the local scattering, attenuation, and amplification of seismic wavefields. Wave attenuation tends to occur in valleys, and amplification occurs near peaks and high up on ridges (Dunham et al., 2022, but the details of this here are unknown. Another possible influence could have been deep bedrock weathering and fracture structure, such as has been implicated in the Chamoli, Uttarakhand, India ridge failure on February 7, 2021 (Richardson and Reynolds, 2000; Reynolds et al., 2021; Shugar et al., 2021). We therefore call for seismic wave field modelling to better understand the precise structure of the 1970 earthquake.

## 5 Conclusions

Using the most recent and complete databases of known earthquakes and GLOFs for Perú and Bolivia, we have demonstrated that, since AD1900, only one earthquake (out of a total of 59 spatially intersecting with Andean glacier lakes; Cook et al., 2016; Wood et al., 2021) is directly associated spatially and temporally with a glacier lake outburst flood. Besides the anomalous 1970

Perú earthquake, evidence for earthquake triggering of GLOFs is (at best) speculative, and largely associated with concurrent mass movements (Table 1).

Our discussion of the lakes which experienced a GLOF resulting from the 1970 earthquake (including Supporting Information Text S2), has focused on moraine dammed lakes; whilst the majority of lakes in Perú are bedrock dammed, moraine dammed lakes are typically larger (0.09km$^2$ in size, with a total volume of 4.09km$^3$) than bedrock dammed lakes (at <0.05km$^2$, with a total volume of only 3.62km$^3$) (calculated from data presented in Wood et al., 2021). We make assumptions about the dam composition and the physical characteristics of the moraines, but present these as working hypotheses at this stage, and whilst recognising that further analysis would be invaluable to the community, this requires considerable further investigation. The same would apply for the specific earthquakes characteristics which would cause a moraine to fail: what characteristics favor a lack of failure, and what could be expected to happen in the case of a bedrock dammed lake? Understanding how earthquakes act on different lake types would also be invaluable to the wider community and for the development of climate resilient protocols, deserving substantial further consideration.

Climate change and the retreat of glaciers is resulting in more lakes, and unstable slopes above them, to develop in seismically active regions, adding uncertainty as to how future lakes might become destabilised by catastrophic mass movements. Understanding site-specific conditions at the 1970 GLOF sites is an important area for future research, particularly moving forwards and thinking of the climatological context of GLOFs in the Andes; specifically in quantifying the amount of precipitation before and after the earthquake occurred, or whether there were prolonged hot or dry periods that might cause thawing of permafrost in the mountain headwalls or saturation of the moraine dams. Earthquakes are currently a frequently used component in GLOF hazard-ranking schemes globally, but our results demonstrate that the empirical evidence to support this is lacking. Other factors are likely more important in determining when and where GLOFs occur. We argue that the focus for future hazard assessments should be on understanding other key GLOF drivers.

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**Open Research**
Data and materials availability:
Earthquake data are available to download from the USGS Earthquake Catalog. The search critereia used were:

- Earthquake magnitude: 4+
- Start time: 1900-01-01 00:00:00
- End time: 2021-05-17 00:00:00
- Spatial extent: -61.172, 0.176; -82.661, -21.085
- Event type: Earthquake
- Search URL: https://tinyurl.com/shaking-up-assumptions

GLOF data are available through Emmer et al. (2022b).
Data were analysed in R-Statistical Software (https://www.r-project.org/).

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