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# Earthquake-induced landslides in Norway

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**Abstract.** Norway is located in an intraplate setting with low to moderate seismicity. The mountainous landscape leads to a high level of landside activity throughout the country. Earthquake-induced landslides (EQIL) are common in seismically active areas, but there are only few studies of EQIL in intraplate regions. We systematically analyse all earthquakes in Norway with magnitudes ≥ 4.5 in the time period 1800-2021 CE. For each event we search for reports of EQIL in the available macroseismic data and in the Norwegian landslide database. We furthermore consider precipitation data from the Norwegian Climate Service Centre to evaluate the role of precipitation in the triggering of the identified potential EQIL. Through this approach, we identified 22 EQIL that have been triggered by 8 earthquakes in the magnitude range 4.5 – 5.9. The events are widely distributed in northern and southern Norway. The maximum landslide distance limits and landslide-affected areas are much larger than those found in empirical studies of global datasets, and in agreement with data from other intraplate regions. For three of the earthquakes, it seems that landslide triggering was due to a combined effect of precipitation and earthquake ground shaking. Our observations confirm that intraplate earthquakes have potential to trigger EQIL over large distances, most likely due to the low ground motion attenuation in such regions. Slope susceptibility seems to be another important factor in the triggering. Our conclusions demonstrate the importance of considering EQIL potential in earthquake risk management in intraplate regions.

## 1 Introduction

Norway, with its steep, high-relief terrain and northern location, is prone to all types of slope failures with rockslides, snow avalanches and debris slides being the most common. Since the 1860s, more than 2000 people have been killed by slope failures in Norway (Jaedicke et al., 2009). The vast majority of slope failures in Norway are triggered by precipitation or snow melt, while earthquakes, as in many intraplate settings, have not been considered a relevant trigger mechanism. There are several examples from international studies demonstrating that there is a potential for earthquake-induced landslides (EQIL) also in intraplate settings (e.g. Keefer, 2002; Jibson and Harp, 2012), but the characteristics of intraplate EQIL, e.g. in terms of maximum epicentral distances of induced landslides or size of the EQIL-affected area, are still poorly understood. Also in Norway there are a few reports of EQIL in the literature (e.g. Mäntyniemi et al., 2021), but such events have never been searched for systematically. In this study we perform such a systematic search to establish a list of

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landslides induced by earthquakes with magnitude M≥4.5 in Norway and contribute to the general understanding of EQIL in intraplate areas.

We first describe what is currently known about EQIL with a special focus on intraplate areas and provide a brief outline of the seismicity and landslide activity in Norway. We then describe the methods and data used for our systematic search for EQIL before presenting the results from the individual events. Finally, we discuss our results in relation to studies from other intraplate regions.

### 1.1 Earthquake-induced landslide studies

Several studies of EQIL have been published over the last decades, based on global, regional, or local datasets, but mostly focusing on areas with high seismicity (e.g. Bommer and Rodriguez, 2002; Delgado, 2011a; Hancox et al., 2002; Jibson and Tanyas, 2020; Keefer, 1984; Keefer, 2002; Papadopoulos and Plessa, 2000; Prestininzi et al., 2000; Rodriguez et al., 1999; Tadard et al., 2010). In his pioneering study, Keefer (1984) worked on a global dataset of EQIL triggered by 40 earthquakes to determine minimum magnitudes for landslide triggering as well as relations between earthquake magnitude and landslide area and maximum epicentral and fault distance to EQIL for different categories of landslides (disrupted, coherent and lateral spreads and flows). He suggested that differences in attenuation have little effect on the area of triggered landslides, however, his database contains only very few events from intraplate areas and/or areas with low attenuation. Keefer's (1984) study has been updated, including more data from more diverse tectonic areas, in a number of publications (e.g. Delgado et al., 2011a; Keefer, 2002; Rodriguez et al., 1999). Delgado et al. (2011a) study a database of EQIL triggered by 270 earthquakes, 150 of which are considered to have high-quality data. They find that most events follow the EQIL areas and distance limits suggested by Keefer (1984), but that there are outliers, mostly disrupted or coherent landslides triggered by earthquakes in the low-to-moderate magnitude range.

In the last decade there have been several studies focusing on landslide triggering in the outermost distance limits (e.g. Jibson and Harp, 2012; 2016; Wistuba et al., 2018). Such extreme triggering is most often observed in intraplate areas with low ground motion attenuation and high slope susceptibility. Events that are well known to have triggered landslides at large distances include the 1988 Saugenay (M = 5.8) earthquake in Canada (Lefebvre et al., 1992), four earthquakes in the Colorado Plateau between 1988-1994 with magnitudes in the range 4.6 - 5.7 (Keefer, 2002) and the 2011 Mineral, Virginia (M = 5.8) earthquake (Jibson and Harp, 2012). The 2011 Mineral, Virginia earthquake triggered landslides at distances up to 245 km. Jibson and Harp (2012) suggest that, in addition to the low level of ground motion attenuation, a factor explaining the long EQIL distance limit may be the detailed level of investigation for this and other recent events.

Delgado et al. (2011b) study EQIL in southern Spain and find that whereas landslide distance limits are within the limits of Keefer (1984) for larger events, the smaller events (M ≤ 5) tend to trigger landslides at larger distances than predicted by Keefer (1984). The authors conclude that slope susceptibility is an important factor for such small events. Also Tatard et al.

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(2010), analysing landslide triggering by precipitation and earthquakes in six different regions, emphazise that the readiness of a slope for failure is an important factor in EQIL triggering. A few studies have evaluated the potential for combined triggering of landslides by earthquakes and water, indicating that long-distance EQIL triggering often occurs when slopes are water saturated, e.g. due to intense rainfall or snow melt (e.g. Hancox et al., 2002; Porta et al., 2021; Sassa et al., 2007).

The vast majority of EQIL studies have focused on EQIL triggered by large earthquakes in active tectonic areas. The studies described above are starting to shed some light on EQIL triggering in areas of moderate to low seismicity, but available data is still very limited, and there is a continued need for expanding the dataset to better understand the properties and causes of EQIL at large distances from smaller earthquakes in intraplate areas.

### 1.2 Seismicity of Norway

The Norwegian mainland is located far from active plate boundaries and the level of seismicity is low-to-moderate. Small earthquakes (M<4.0) occur regularly, while larger events occur at intervals of several years. The largest historical earthquake in mainland Norway occurred on 31 August 1819 in Nordland, northern Norway, with a magnitude of 5.9. This event triggered several rock falls in the epicentral area (Mäntyniemi et al., 2020). The event was widely felt in Norway, Sweden, Finland and northern Russia, and caused some damage in the epicentral area. In total, the Norwegian National Seismic Network (NNSN; www.skjelv.no) has reported 21 earthquakes near the Norwegian mainland with M ≥ 5.0 since 1900. Most of those events are located offshore.

Figure 1 shows an overview of earthquakes recorded by NNSN with a minimum magnitude of 2.0 in the period 1980-2021 CE. In addition to the plate boundary seismicity along the northern mid-Atlantic ridge, there is a high level of seismicity in Nordland, in Northwestern Norway, along graben structures and the continental slope in the North Sea, as well as in parts of Svalbard. There is a moderate level of seismicity along the Oslo graben in eastern Norway and in Skagerrak. Several studies (e.g. Fejerskov and Lindholm, 2000; Fjeldskaar et al., 2002; Olesen et al., 2013) discuss neotectonic deformation and stress-generating mechanisms in Norway. There is general agreement that the present-day stress field originates from a combination of the ridge push force from the mid-Atlantic ridge, sediment loading at the continental shelf, glacial uplift, density contrasts in rocks, and local forces like topography and bedrock geology (Fejerskov and Lindholm, 2000). The relative importance of those mechanisms for the stress generation is, however, still an area of active research.

During the last deglaciation (~15,000-9,000 cal. yr BP), rapid melting of the continental ice sheet and the associated isostatic uplift led to a high level of seismicity in Norway. It is assumed that earthquakes on postglacial faults may have triggered rock avalanches along fjord areas after the last deglaciation (Blikra et al., 2006). Since then, the seismicity rate and rate of isostatic uplift have decreased. The postglacial uplift at the west coast of Norway is presently at a few millimetres a year. Isostatic uplift is over the last centuries considered to be a minor mechanism for earthquake generation in Norway (Olesen et al., 2013).

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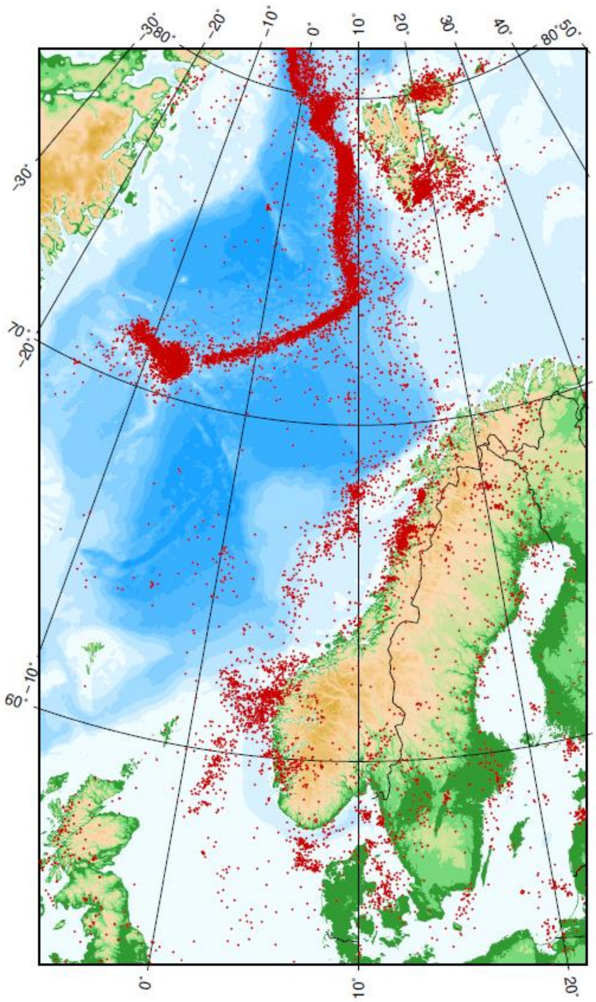


**Figure 1: Earthquakes with M ≥ 2.0 recorded by NNSN in the period 1980-2021 CE.**

### 1.3 Landslides in Norway and their trigger mechanisms

The Norwegian landscape, with deep fjords and steep valleys, has developed through cycles of glaciations and interglacials over the last 2.58 million years. The western and northern parts of Norway are characterized by steep mountains and valley sides, whereas eastern and central Norway are dominated by more low-relief topography with thicker and more continuous sediment sequences. The landscape-forming processes, in particular during the Quaternary period, have made Norway prone to landslides of almost any type.

Rockfalls and rockslides are the most frequent types of landslides in Norway, that regularly cause damage to roads and other infrastructure (Jaedicke et al., 2009). Rock avalanches are much rarer, but have widespread damage potential, especially if

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runout is into a lake or fjord with potential to generate a tsunami. Since 1900, Norway has been exposed to three catastrophic tsunamis caused by rock avalanches in 1905, 1934, and 1936, killing a total of 174 people (Harbitz et al., 2014). Various types of soil failures (e.g. debris flows, debris avalanches) are also common in Norway, leading to frequent damage and loss of [illegible]. Typical trigger mechanisms for landslides in rock and soil in Norway are long-term or heavy rainfall or rapid snow melting, leading to high water content in the bedrock and/or sediment cover. Other triggering factors include various types of weathering, erosion, and seismic activity (Høeg et al., 2014).

Clay slides and quick clay slides are most common in South-eastern and Mid Norway, due to the thick clay sequences that were mainly deposited during the last deglaciation. Trigger mechanisms of (quick) clay slides include both natural causes (e.g. river erosion or long-term or heavy rainfall) and human causes (e.g. construction [illegible]).

There are only very few documented cases of EQIL in Norway, and those have been published in connection with seismological studies of large earthquakes. Mäntyniemi et al. (2020) present reports of several EQIL in connection with the 1819 M5.9 Lurøy earthquake. Mäntyniemi et al. (2021) furthermore summarize environmental effects, including EQIL, triggered by the 1904 M5.4 Oslofjord earthquake. On a longer time scale, Blikra et al. (2002) argue that rock avalanche events in North-West Norway around 3000 cal. BP are linked to the Berill Fault and potentially caused by a M6.5 earthquake along that fault. However, with the data available, such a link is necessarily somewhat speculative.

## 2 Methods

In order to systematically search for EQIL in Norway, we searched through available datasets of earthquake and landslide information, looking for events that are co-located in time and space. We describe the approach for the event search here, the individual datasets are described in detail in Sect. 3.

We extracted earthquakes with M[illegible] from the earthquake database of the Norwegian National Seismic Network (NNSN). For each event, we then searched for reports of triggered landslides in the macroseismic archives at University of Bergen (UiB) and the Scandinavian Earthquake Archive (SEA). We also searched the Norwegian landslide database (NLD) for events coinciding in time and location with the earthquakes, as well as for events in the database that were mentioned in the commentary to be associated with earthquakes.

For each earthquake-landslide match, we critically evaluated the likelihood of the landslide being triggered by the earthquake. In many cases, it was evident from the descriptions that there was a triggering relation, in other cases the link is more uncertain. We excluded cases where descriptions were speculative, if it was uncertain if the ground shaking described was due to an earthquake or the landslide itself, or if the landslide was triggered several days after the earthquake. Some examples are given in Sect. 4. A minimum requirement for including events in our list of Norwegian EQIL is that we have (at least approximate) locations of both the landslide and the earthquake triggering it, as well as an estimate of the

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earthquake magnitude. In practice that means that we need independent reports of the earthquake, as a few landslide reports are usually insufficient to determine location and magnitude of an earthquake.

The most important trigger mechanism of landslides in Norway is precipitation, and even for landslides that are considered earthquake-induced, precipitation prior to the earthquake may have made slopes more prone to failure. In order to evaluate the relative importance of precipitation and ground shaking in the triggering of events, we downloaded precipitation data for the time of each triggered landslide from the Norwegian Centre for Climate Services (www.seklima.met.no) and discuss the observations in relation to the triggered landslides.

## 3 Data

Earthquake information is extracted from the openly available earthquake database of NNSN. The dataset is based on data processing at UiB considering data from the NNSN, currently 42 stations in mainland Norway and the Norwegian Arctic islands, as well as data from stations in the surrounding countries. We extracted all earthquakes with M≥4.5 (considering here only $M_L$ and $M_W$) at or near the Norwegian mainland in the time period 1800-2021 CE. Whereas smaller events may trigger landslides as well, we select the lower magnitude threshold of M=4.5 in order to have a systematic overview of the landslide-triggering-potential of earthquakes nationally. The study area was defined as the Norwegian mainland, including nearby parts of the North Sea, Sweden, Denmark, and Finland (polygon in Fig. 2). Within this region, we found 78 earthquakes with M≥4.5 in the time period 1800-2021 CE, as presented in Fig. 2 and Appendix A.

The macroseismic archive at UiB contains earthquake information for Norway for the last two centuries. The archive contains systematically collected letters, questionnaires, newspaper articles and other reports of felt earthquakes, for many events several hundred pages of materials are available. For some events, additional information (newspaper articles, macroseismic intensity maps, etc.) is available through the Scandinavian Earthquake Archive (SEA; ICG, 2003). For all events in Fig. 2, the available materials in the macroseismic archive and the SEA were read to check for reports of triggered landslides.

The Norwegian landslide database (NLD) is maintained by the Norwegian Water Resources and Energy Directorate (NVE) and provides the most comprehensive listing of Norwegian landslides with more than 80.000 events currently listed. Despite the high number of events, the database in not complete, and the precision and level of detail in the information included varies significantly among the events. For each of the 78 earthquakes with M≥4.5, we searched the NLD for landslides occurring within 5 days and 250 km of the earthquake. We also made a text search for events with the word "earthquake" ("*jordskjelv*" in Norwegian) in the commentary. That was the case for 23 events. For each of the identified landslides we then evaluated whether the spatial and temporal links, as well as the information provided in the commentary, were sufficient to indicate a triggering relation.

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Precipitation data were downloaded from the Norwegian Centre for Climate Services who offer observations from weather stations throughout Norway through the online platform "*Seklima*". For each earthquake (when available), 24-hour precipitation data were downloaded for the time period prior to the event and visually inspected to evaluate the potential role of precipitation in landslide triggering.

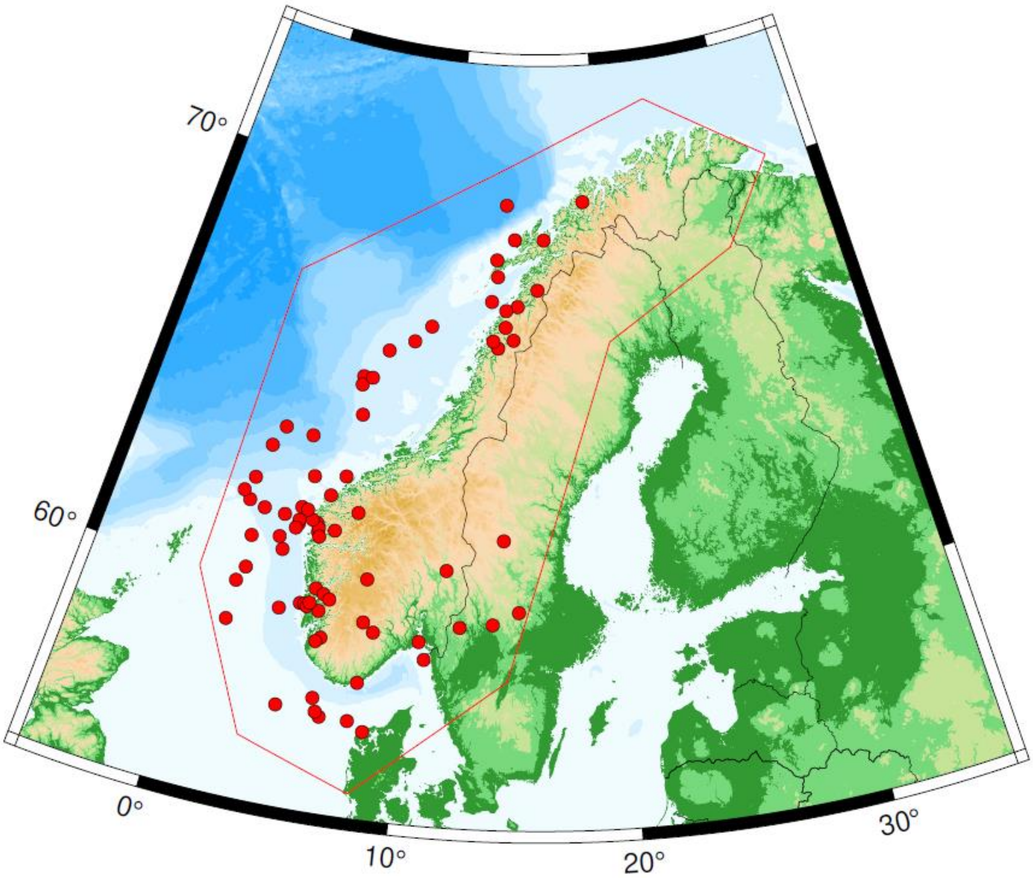


**Figure 2: Earthquakes with M≥4.5 near the Norwegian mainland in the period 1800-2021 CE, which are checked for reports of EQIL. The red polygon outlines the area within which the earthquake search was performed.**

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## 3 Results

Through the systematic search of available earthquake and landslide data we identified 22 EQIL that were triggered by 8 different earthquakes in Norway in the period 1800-2021. The events are presented in Fig. 3, with details on locations and epicentral distances given in Table 1. We discuss each event and the background data in the following sections.

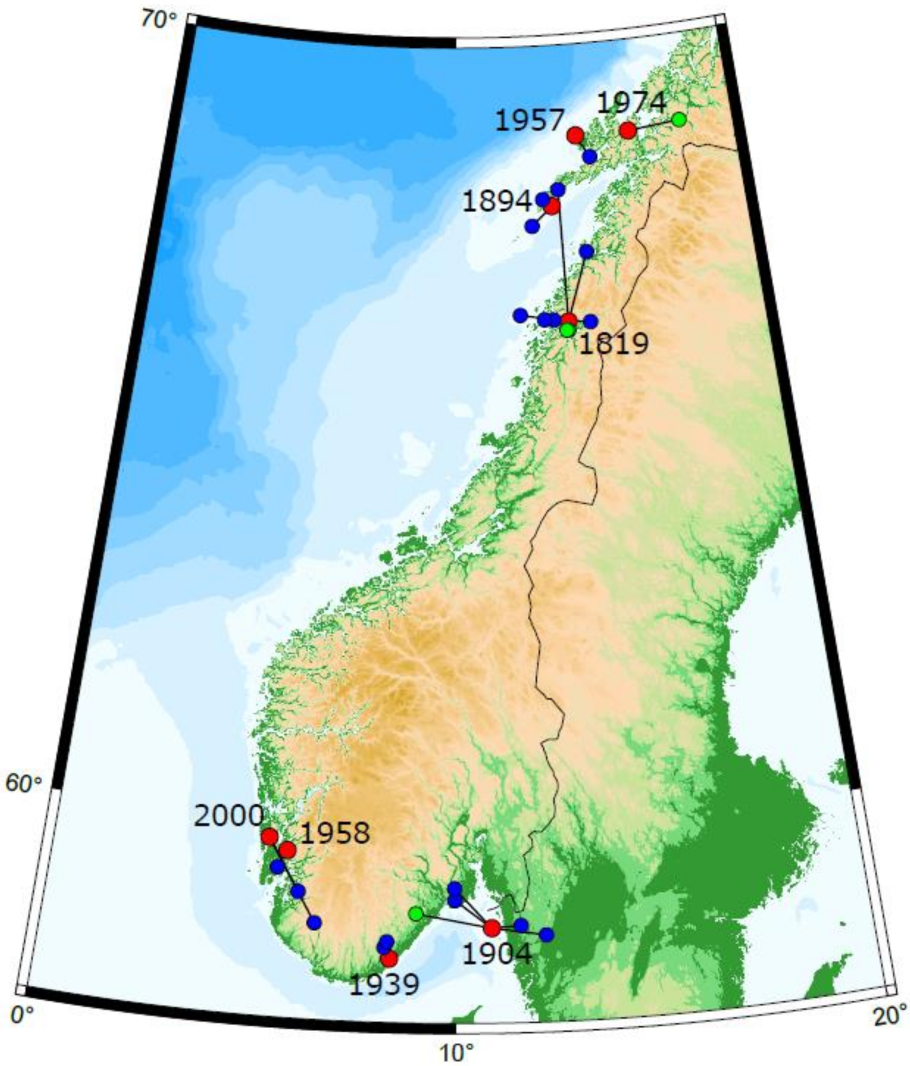


**Figure 3. Norwegian EQIL identified in this study. Red dots are earthquake locations, blue dots are rock falls and green dots are slides. Lines connect each EQIL to the triggering earthquake.**

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180 **Table 1. Earthquake induced landslides in Norway. * indicates an uncertain event. References: a: Mäntyniemi et al 2020; b: NLD; c: Mäntyniemi et al., 2021; d: macroseismic archive at UiB**

| **Earthquake** | | | **Landslide** | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Date Magnitude** | **Latitude °N** | **Longitude °E** | **Type** | **Location** | **Latitude °N** | **Longitude °E** | **Distance (km)** | **Reference** |
| 1819/08/31 5.9 ($M_L$) | 66.39 | 13.63 | Clay slide | Dilkestad | 66.28 | 13.56 | 12 | b |
| | | | Clay slide | Hemnes | 66.28 | 13.62 | 13 | a, b |
| | | | Rockfalls | Aldersundet | 66.42 | 13.16 | 21 | a, b |
| | | | Rockfalls | Lurøy | 66.43 | 12.86 | 35 | a, b |
| | | | Rockfalls | Ranen | 66.37 | 14.34 | 36 | a |
| | | | Rockfalls | Træna | 66.50 | 12.08 | 70 | a, b |
| | | | Rockfalls | Bodø | 67.28 | 14.38 | 104 | a |
| | | | Rockfalls Clay slides | Buksnes | 68.11 | 13.55 | 191 | b |
| 1894/07/23 5.4 ($M_L$) | 67.9 | 13.3 | Rockfall | Moskenes | 67.99 | 13.00 | 16 | b |
| | | | Rockfall | Værøy | 67.65 | 12.59 | 41 | b |
| 1904/10/23 5.4 ($M_S$) | 58.69 | 10.86 | Rockfall | Bullaren, Sweden | 58.717 | 11.567 | 40 | c |
| | | | Rockfall | Salsås | 59.04 | 9.97 | 65 | c |
| | | | Rockfall | Jordstøyp | 59.19 | 9.96 | 76 | c |
| | | | Rockfall | Bollungen, Sweden | 58.590 | 12.167 | 76 | c |
| | | | Soil/Clay slide | Gjerstad | 58.87 | 9.02 | 108 | c |
| 1939/10/09 4.6 ($M_w$) | 58.3 | 8.4 | Rockfall | Dalane | 58.44 | 8.27 | 17 | d |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Rockfall | Herefoss | 58.51 | 8.33 | 24 | d |
| 1957/06/22 4.5 (Ms) | 68.8 | 14.3 | Rockfall | Melbu | 68.51 | 14.75 | 37 | b |
| 1958/08/06 5.4 ($M_w$) | 59.6 | 5.8 | Rockfall* | Tysvær | 59.38 | 5.58 | 28 | d |
| 1974/04/28 4.7 ($M_L$) | 68.8 | 16.2 | Clay slide | Salangsdalen | 68.86 | 18.08 | 75 | b, d |
| 2000/08/12 4.5 (ML) | 59.748 | 5.329 | Rockfall | Tysdalsvatnet | 59.09 | 6.13 | 85 | b |
| | | | Rockfall (minor) | Stakkavatnet | 58.71 | 6.57 | 136 | d |

### 3.1 The 31 August 1819 Lurøy, Nordland, earthquake

The 1819 Lurøy earthquake is the largest earthquake in Fennoscandia in historical times. Several studies (e.g. Muir Wood, 1988; Bungum and Olesen, 2004; Mäntyniemi et al., 2020) have analysed the macroseismic reports from the event to determine its location and magnitude, most recently Mäntyniemi et al. (2020) reassessed intensities, including also a number of previously unknown observations, and found a magnitude of 5.9 ± 0.2 for the event. The largest observed intensity was VIII. It is well documented in the previous studies that this event triggered several landslides. The location of the event has never been evaluated using state-of-the-art methods. Muir Wood (1988) lists a location of the event near Mo i Rana (66.4N, 14.4E), which is to the east of the area experiencing the strongest effects of the earthquake. It is outside the scope of this study to perform an in-depth evaluation of the location of this earthquake, but in order to have more reliable landslide distance limits, the event was relocated with the BOXER code (Gasperini et al., 1999; 2010) using the intensities assigned by Mäntyniemi et al. (2020). We thereby obtained a location (66.39N, 13.63E) that is in better agreement with the macroseismic observations. We will use this new location for the event in this study.

The macroseismic reports from the earthquake have already been thoroughly analysed and presented in previous studies. Reports from the epicentral area are mostly available in contemporary newspapers, describing very strong shaking and minor to moderate damages (see Mäntyniemi et al., 2020 for a detailed description, including English translations of all reports).

In this study we used the macroseismic reports with associated coordinates listed by Mäntyniemi et al. (2020) as a starting point. We quality checked the locations of reported landslides and moved some to more meaningful locations (see comments in Table 2 for details). The NLD contains some of the reported landslides and lists two additional landslides that are not mentioned by Mäntyniemi et al. (2020). There are several reports of rockfalls and clay slides causing damage to the soil and farmland. There are some mentions of houses almost being hit by falling rocks. A summary of the landslides that were identified for this earthquake is given in Table 2, the locations are presented in Fig. 4. We find at least eight landslides that were triggered by the 1819 earthquake, at distances up to 191 km from the epicentre.

There is no precipitation data available for the region at the time of the earthquake, but several macroseismic reports mention that the earthquake happened after a 3-week period of rainy weather. In that regard, water saturation of the slopes is expected
205 to have contributed to their instability. However, based on the magnitude of the earthquake and the descriptions available, the earthquake is expected to be the main trigger of the reported landslides.

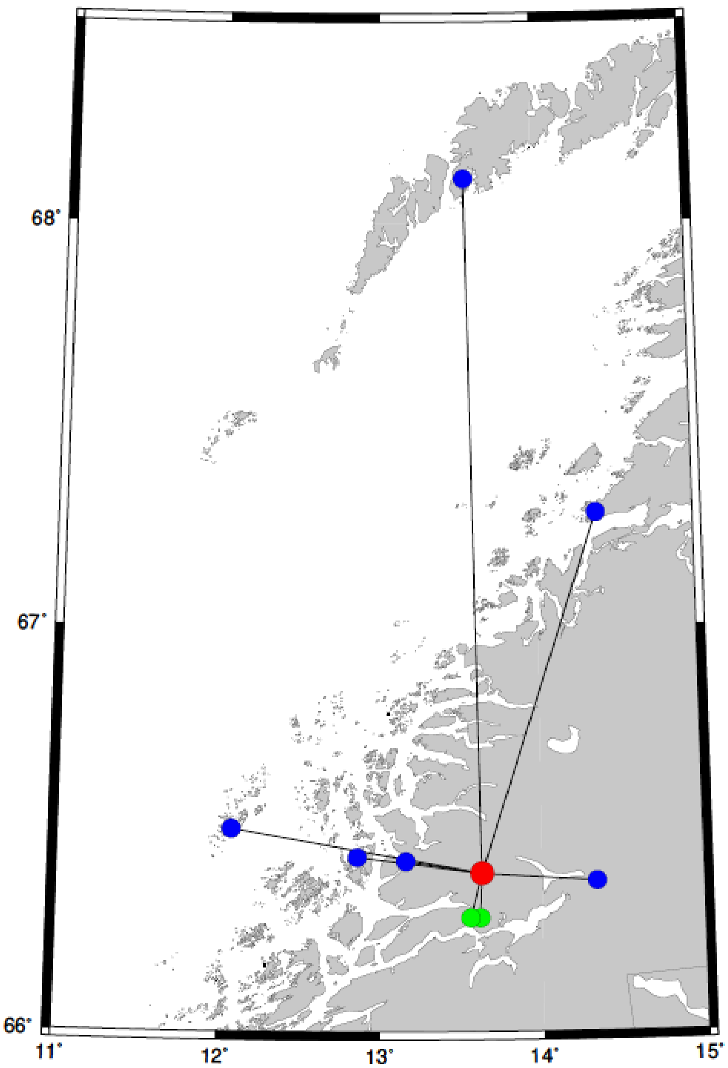


**Figure 4. Landslides triggered by the 1819 Lurøy earthquake. Red dot is the epicentre of the event, blue dots are rockfalls, green dots are clay slides.**

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**Table 2. Landslides reported in connection with the 1819 Lurøy earthquake. Locations are from Mäntyniemi et al. (2020) if not stated otherwise. Epicentral distance is relative to the BOXER location (66.39N, 13.63E).**

| Location | Type | Lat | Lon | Epicentral distance | Comment |
|---|---|---|---|---|---|
| Aldersundet | Rockfalls | 66.42 | 13.16 | 21 | Referred to as Lia in NLD. The location provided (66.42N 13.14E) is in the fjord, and has been adjusted to move to the slope on land. |
| Bodø | Rockfalls | 67.28 | 14.38 | 104 | Not in NLD |
| Hemnes (Storstrand) | Clay slide | 66.28 | 13.62 | 13 | Referred to as Storstrand in NLD, NLD location is used as it fits descriptions better. |
| Lurøy | Rockfalls | 66.43 | 12.86 | 35 | Referred to as Lurøy gard in NLD. |
| Ranen | Rockfalls | 66.37 | 14.34 | 36 | Not in NLD. |
| Træna | Rockfalls | 66.50 | 12.08 | 70 | Location has been moved to the central part of the Træna island. |
| Buksnes | Rockfalls, Clay slides | 68.11 | 13.55 | 191 | Only in NLD. |
| Dilkestad | Clay slide | 66.28 | 13.56 | 12 | Only in NLD. |

### 3.2 The 23 July 1894 Lofoten earthquake

The 1894 earthquake was located near the Lofoten islands in northern Norway with a magnitude of $M_W$=5.4. The event was felt in the Nordland district with a maximum intensity of VII and also over large parts of central Norway. The NLD reports that several large rockfalls occurred at the Moskenes and Værøy islands in Lofoten in direct connection with the earthquake. The maximum distance to the triggered landslides is 41 km. There is no weather data available from the Lofoten area at that time and it is thus not possible to evaluate the role of precipitation in triggering the rockslides. It is considered highly likely that the earthquake played a significant role in triggering the rockfalls.

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### 3.3 The 23 October 1904 Oslofjord earthquake

The 1904 Oslofjord earthquake is also a well-known and thoroughly studied Norwegian earthquake due to its location close to the capital city of Oslo. It occurred on a Sunday morning during church hours and was strongly felt causing some panic in Oslo but only minor damages. The event had a magnitude of 5.4 and was located at 58.69N, 10.86E (Bungum et al., 2009), the maximum observed intensity was VII. Environmental effects caused by the earthquake, including induced landslides, were recently summarized by Mäntyniemi et al. (2021). We base our analysis on those findings.

The landslides induced by the 1904 earthquake are presented in Table 1 and Fig. 3. In Norway, the NLD reports two rockfalls at Salsås and Jordstøyp near Larvik, mentioning that more slides occurred in the same area. An 18-20 wide soil or clay slide was reported by Kolderup (1905) to have occurred along a riverbank near Gjerstad. In Sweden there are reports of two rockfalls near Bullaren and Bollungen. Rockfall activity is reported to have continued near Bullaren in the days after the earthquake, culminating in a large landslide during the night between 29-30 October, 6 days after the earthquake. There are also reports of a land subsidence near Väddö, 25 km from the earthquake (Mäntyniemi et al., 2021), but this event has not been included in the list as it is not a fully developed landslide. We thus list five landslides triggered by the 1904 earthquake, at a maximum distance of 108 km.

Figure 5 presents precipitation data from four weather stations located around the epicentral area, near the observed landslides. It is seen that there was relatively little precipitation in the area on the days prior to the earthquake, supporting the earthquake being the main trigger of the slides.

In addition to the landslides listed above, there are reports in the NLD of a large rockfall crossing the railway passing through Etnedal on 25 October 1904, two days after the large earthquake, at approximately 230 km distance. It is mentioned that aftershocks had been strongly felt in the area on that day, and it is speculated that the landslide is earthquake-triggered. The precipitation data (Fig. 5) shows that there was significant rainfall on 25 October (18 mm in 24 hours at station Biri near Etnedal) that may have contributed to triggering the rockfall. We find the triggering relation is uncertain, a combined effect of precipitation and ground shaking is likely, and the event is not included in our list.

### 3.4 The 9 October 1939 Lillesand earthquake

The 1939 earthquake is listed in the NNSN database with $M_W$=4.6 and a location near Lillesand between Kristiansand and Arendal. The event was felt over a large area in southern Norway with a maximum intensity of V. In one questionnaire in the macroseismic archive at UiB, which is accompanied by a letter describing the observations in more detail, it is reported that at Dalane in Herefoss, the earthquake was clearly felt. On the day after the earthquake, on 10. October 1939, a rock fall was observed 3-400 m from the houses at Dalane, at 17 km distance from the earthquake. Large blocks are reported to have fallen down, one of them the size of a house. About 70 m of forest is reported to have been destroyed. There are also reports of rocks falling down on the road along the Western part of Herefossfjorden, between Odden and Herefoss Gård in Herefoss,

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at ca. 24 km distance from the earthquake epicentre. There are no reports in the NLD of landslides in connection with this earthquake.

Precipitation data from October 1939 at the meteorological station in Herefoss is presented in Fig. 5. The days prior to the earthquake are relatively dry with 7.8 mm rainfall on 7. October. Rainfall is observed on 9.-10. October (15.9 mm in total during the two days). Whereas that may have increased the susceptibility of the slope, it is considered insufficient to argue against the earthquake being the main trigger.

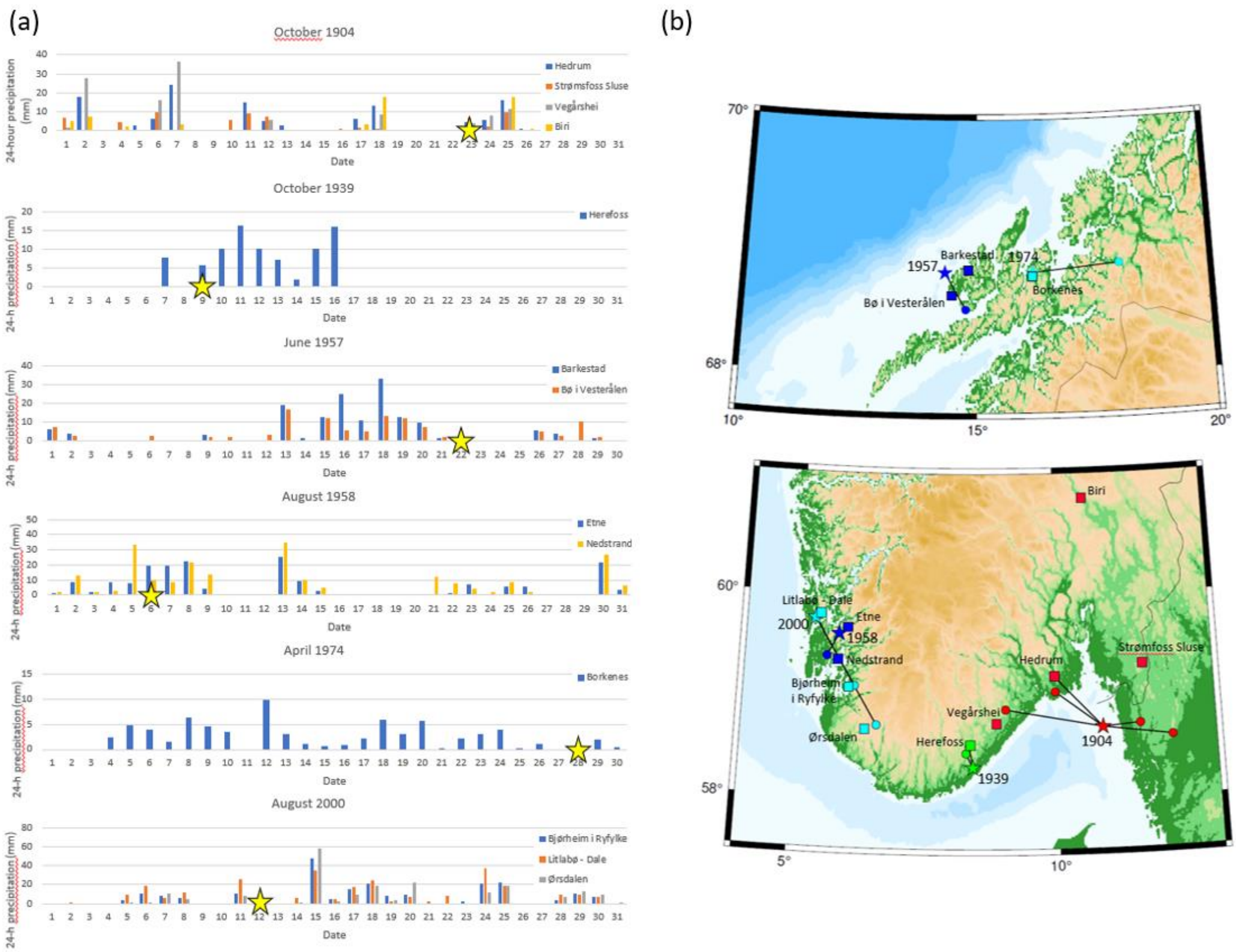


**Figure 5. a) Precipitation observed around the times of the earthquakes inducing landslides. B) Locations of the weather stations shown in a) (squares), earthquake epicentres (stars) and EQIL (circles). Lines connect EQIL to the epicentre of their triggering earthquake. Colours are the same for data referring to a given earthquake.**

### 3.5 The 22 June 1957 Vesterålen earthquake

The 1957 earthquake was located just offshore Langøya in Vesterålen and had a magnitude of $M_L$=4.6 and maximum intensity V. The event was felt throughout Lofoten and Vesterålen. The NLD reports a rockfall close to Melbu with a very large block landing only about 20 m from a house. It is mentioned that there were several rockfalls in connection with the earthquake, but no further information is given on their locations. Melbu is at 37 km distance from the earthquake epicentre. There are no reports of EQIL in the macroseismic archive.

Figure 5 shows precipitation data from two stations on Langøya, at similar distances from the earthquake, in June 1957. There was no precipitation on the day of the earthquake, but it happened after a period of about a week of rainy weather. The ground is thus expected to have been water saturated making it more prone to failure. However, the amount of rainfall is not extraordinary and several rockfalls were observed, therefore the earthquake is expected to have had a major role in triggering the rockfalls.

### 3.6 The 6 August 1958 Ølen earthquake

On 6 August 1958, a magnitude $M_W$=5.4 earthquake occurred near Ølen in southwestern Norway. The event was felt throughout southern Norway with a maximum observed intensity of V-VI. The macroseismic archive at UiB contains a newspaper article from the local newspaper Haugesund Dagblad stating that a large rockfall occurred in Tysvær on the day after the earthquake and speculating that the earthquake was the trigger. The distance from Ølen to Tysvær is 28 km. There are no reports of landslides in connection with the earthquake in the NLD. There is no further information to be found on the landslide, and the triggering relation is considered uncertain.

Precipitation data from surrounding weather stations (Fig. 5) show that the rockfall occurred after several days of rainy weather. The amount of precipitation is not extraordinary, but slopes are expected to have been water saturated and thus more prone to failure. We expect that this rockfall was triggered by the combination of precipitation and ground shaking. We choose to include the event in our list of EQIL, noting the uncertainty and limited information available.

### 3.7 The 28 April 1974 Kvæfjorden earthquake

The 1974 earthquake was located near Kvæfjorden in northern Norway with magnitude $M_W$=4.9. The event was felt throughout the Nordland region with maximum intensity V. Both the macroseismic archive and the NLD contain reports of a large clay slide that was triggered in Salangsdalen, at 75 km distance from the epicentre, immediately after the earthquake. The slide temporarily dammed the river Salangselven leading to flooding of the road running along the river. The NLD also lists a debris slide very close to the clay slide without any description of the event. Due to the proximity of the two events and the lack of information, the debris slide has not been included as a separate event, but it is expected that several slope failures have occurred along the Salangsdalen valley in connection with the earthquake.

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Precipitation data from the area at the time of the event (Fig. 5) show that there had been a steady, low level of precipitation during the days before the earthquake without any intense precipitation event. This supports the earthquake being the main trigger of the landslides.

### 3.8 The 12 August 2000 Stord/Bømlo earthquake

The 2000 earthquake was located in the Stord/Bømlo area. The event had a magnitude of $M_L$=4.5 and it was strongly felt in western Norway with maximum intensity V. The NLD contains a report of a rockfall near Tysdalsvatnet, at 85 km distance from the epicentre, noting that the rockfall is most likely triggered by the earthquake. The macroseismic archive contains a questionnaire where the respondent describes a minor rockfall in the mountain near a tourist cabin by Stakkavatnet, at a distance of 136 km from the epicentre.

Precipitation data (Fig. 5) show that there was about 10 mm rainfall on the day before the landslide, which may have made the slope more prone to failure but is not considered sufficient to trigger the slide. We thus conclude that the earthquake was the main trigger of the rockfall.

### 3.9 Events with little documentation

In addition to the events listed above, we have found reports of EQIL that are sufficient to confirm that an EQIL was induced but insufficient to locate the landslide and/or the earthquake. There are also reports of landslides occurring in connection with earthquakes where the documentation is insufficient to argue that the landslide was earthquake-induced. Those cases are listed in the following.

#### 3.9.1 The 15 May 1892 Askvoll earthquake

A large earthquake occurred on 15. May 1892 near Askvoll in western Norway (61.4N; 5.1E). The event is listed in the NNSN database with $M_W$=5.7 and was felt throughout southern and parts of central Norway with a maximum intensity of VI. The NLD lists a clay slide at Bakklandet, Trondheim (63.43N; 10.40E), on 19 May, four days after the earthquake. NLD refers to an article in the newspaper Trondhjems Adresseavis which speculates that the earthquake may have caused cracks in the clay that have later developed into the clay slide. The distance between the earthquake epicentre and the landslide is 350 km. According to the macroseismic reports, the earthquake was weakly felt (I=III) in Trondheim. Precipitation data show that about 10 mm of rainfall was recorded in Tondheim during the days between the earthquake and the landslide. This is not expected to have significantly affected the stability of the clays. We consider it likely that the earthquake has played a role in triggering the clay slide. However, due to the long time and distance between the events, and as cracks following the earthquake are not documented, we choose to not include the event in our list of EQIL in Norway.

### 3.9.2 The 1932 event

The NLD contains a report of a rockfall near Sautso in northern Norway in 1932. The time of year is unknown. According to the NLD report, three people have observed the rockfall immediately after a large earthquake. There are no reports in the macroseismic archives of earthquakes in northern Norway in 1932. The only potential event that can be linked to the rockfall is an event on 14 April 1932 that is shortly mentioned in the SEA to have been felt on the island Bjørnøya, about 500 km north of the landslide location. We consider it likely that the rockfall was earthquake-triggered but cannot include the event in our list of Norwegian EQIL due to lack of information on the earthquake.

## 4 Discussion

The EQIL and their triggering earthquakes are widely distributed in southern and northern Norway (Fig. 3). The events in northern Norway are in one of the most seismically active areas in Norway. The seismicity level in southern Norway is lower, but with higher population density it is more likely that EQIL events are detected and reported. It is somewhat surprising that there are no EQIL in the central parts of the country, especially in Western and North-West Norway where seismicity is high and steep slopes abundant. However, this may be linked to lower population density in those areas and it is expected that EQIL have indeed occurred, though not been reported in the sources studied here.

The landslide distance limits found in this study for Norway are generally much larger than what has been observed from global data (Keefer, 1984; Rodriguez et al., 1999; Delgado et al., 2011a), and fit well the previously observed extreme distance limits from intraplate areas. Figure 6 shows the landslide distance limits found in this study (red dots) together with distance limits from other intraplate earthquakes (1988 Saugenay, Canada (Lefebvre et al., 1992), 1988-1994 Colorado Plateau, USA (Keefer, 2002), 2011 Virginia, USA (Jibson and Harp, 2012); grey dots) and the maximum landslide distance limit curve for disrupted slides and falls obtained by Keefer (1984) (black line). The distance limits suggested by Keefer (1984) severely underestimate the landslide potential of intraplate earthquakes. For magnitudes less than 5.0, the observed intraplate landslide distance limits are up to more than an order of magnitude larger than those suggested by Keefer (1984). For larger events, the difference is up to about half an order of magnitude.

For most of the landslide-triggering earthquakes identified in this study, only one or two EQIL have been identified, and it is not possible to calculate a well-constrained landslide area. The exceptions are the 1819 and 1904 earthquakes, for which 8 and 5 EQIL, respectively, have been identified. Following Jibson and Harp (2012), we determine the landslide area as the area of a polygon containing all landslides triggered by an event. This approach will lead to a minimum-estimate of the landslide-affected area. We obtain a landslide area of 12.000 $km^2$ for the 1819 earthquake and an area of 3700 $km^2$ for the 1904 earthquake. These values are plotted together with the landslide area of the 2011 Virginia, USA earthquake (33400 $km^2$; Jibson and Harp, 2012) and the empirically derived curve of maximum landslide area by Rodriguez et al. (1999) in Fig.

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7. Whereas the number of observations is small, they confirm the systematically larger distance- and area limits for landslide triggering by intraplate earthquakes.

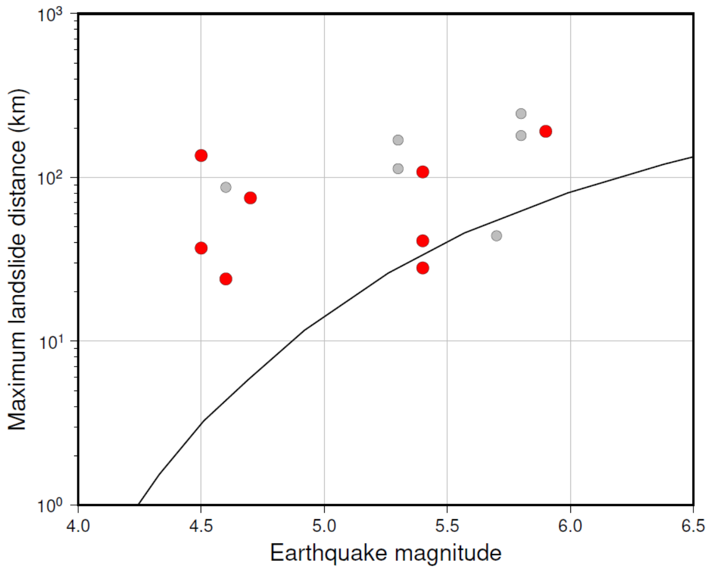


**Figure 6. Landslide distance limits for earthquakes in intraplate areas. Red dots: Norway (this study), grey dots: other areas, black curve: limit for disrupted slides and falls, from Keefer (1984).**

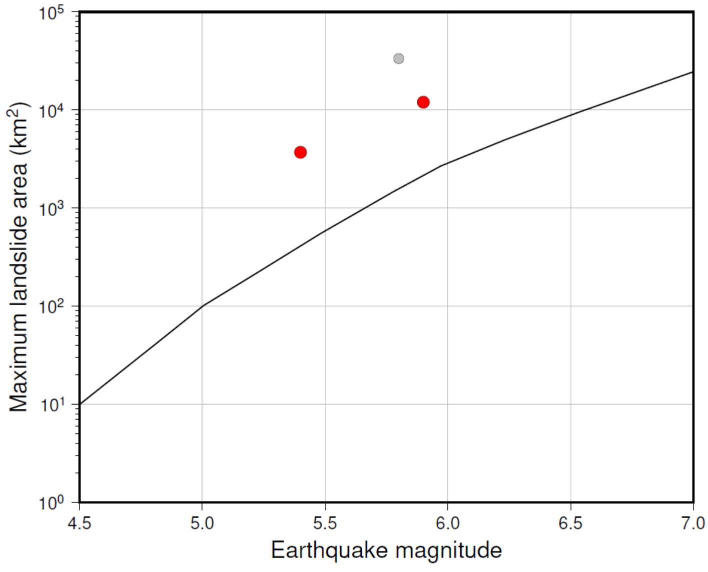


**Figure 7. Maximum landslide area for earthquakes in intraplate areas. Red dots: Norway (this study), grey dot: 2011 Virginia, USA, earthquake, black curve: area limit from Rodriguez et al. (1999).**

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A detailed map of the 1904 earthquake, with earthquake location, EQIL and intensity observations is presented in Fig. 8. All EQIL triggered by that event are located at similar or higher latitude than the earthquake due to the offshore location of the event. It seems plausible that the landslide area may have been larger if there were susceptible slopes located south of the epicentre. The area of highest observed ground motion intensity (I=VII) is elongated in the WNW-ESE direction, and the distribution of observed EQIL follows this trend of the strongest ground shaking well (Fig. 8). Whereas Fig. 8 gives a rough indication of the ground shaking intensity observed near the EQIL locations for the 1904 earthquake, the available intensity data for the remaining landslide-triggering events identified in this study are insufficient to determine generalized threshold intensity levels for EQIL in Norway.

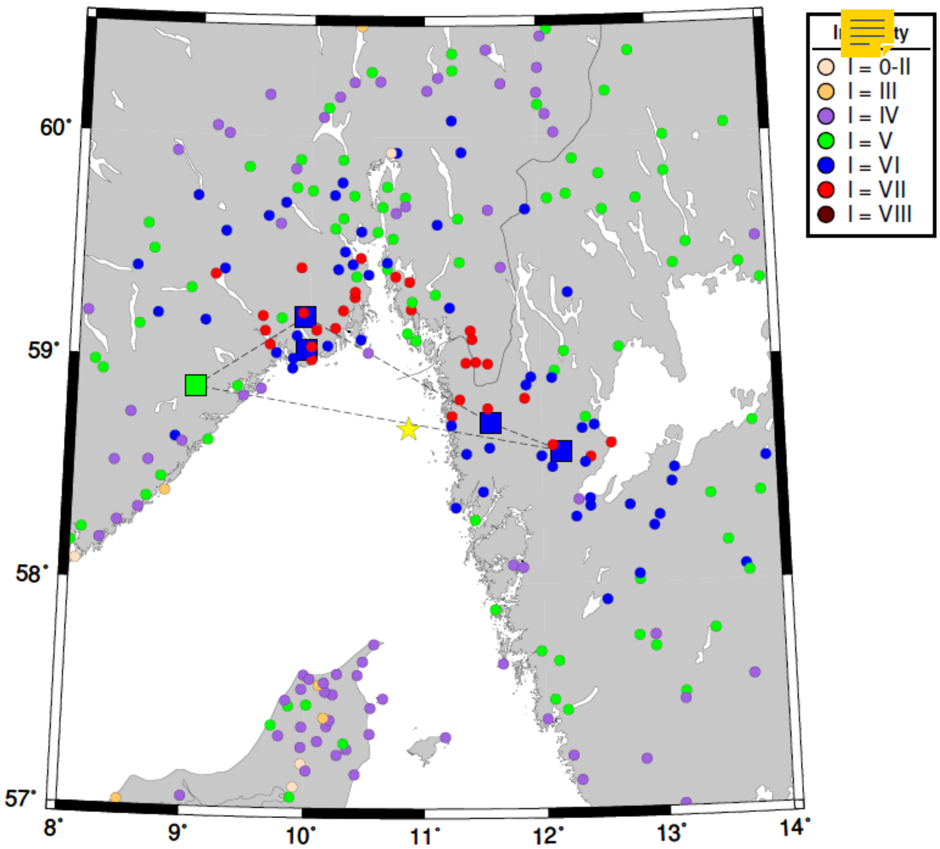


**Figure 8. Data available for the 23 October 1904 M5.4 earthquake. Grey squares are rockfalls triggered by the earthquake, green square is a clay slide. The yellow star shows the epicentre location according to Bungum et al. (2009). Coloured dots are macroseismic intensity observations from Austegard (1975). The dotted polygon shows the landslide area determined from the observed EQIL.**

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From our data, as well as previous observations (Fig. 6, 7), there is little doubt that intraplate earthquakes have the potential to trigger landslides at much larger distances than plate boundary events. This is most likely due to differences in ground motion attenuation leading to stronger ground shaking over a larger area at a given magnitude for intraplate events, as has also been suggested by e.g. Jibson and Harp (2012). Jibson and Harp (2012) also suggest that differences in levels of investigation for historical and more recent earthquakes lead to differences in the landslide distance limits, as recent events have been investigated more thoroughly. Whereas we agree that such differences are most likely present, our dataset is mostly based on historical or macroseismic reports, and it is thus directly comparable to the global studies.

It is expected that slope susceptibility will be important for the extent and distribution of EQIL, especially in intraplate areas where most earthquakes are of low to moderate magnitude. All the landslide-triggering earthquakes in our dataset occurred between April and October. The lack of events during the winter months may be linked to lower slope susceptibility in winter when mountain precipitation is more likely to come as snow and thus will not migrate into the ground. Figure 5 presents precipitation data around the times of the earthquakes, when available. The events in 1957 and 1958 occurred after periods with moderate to intense rainfall which has most likely made the slopes more prone to failure. The same is the case for the 1819 earthquake that, according to the macroseismic reports, occurred after three weeks of intense rainfall (Mäntyniemi et al., 2020).

This study is based mainly on historical reports describing landslide occurrences, mostly written by observers who happened to be at the site of the EQIL. Such reports are often vague, and we do not have information on the shapes and exact sizes of the landslides. However, based on the descriptions available in historical sources, the triggered events are mostly either rockfalls or small rockslides. This is as expected for earthquakes of moderate magnitudes that cause short-duration high-frequency ground shaking, which is most likely to trigger small, shallow landslides. From a hazard perspective this means that EQIL-hazard in Norway is mostly related to smaller landslide events that will impact over limited spatial scales. There are no reports so far of EQIL leading to human casualties in Norway. For extremely susceptible slopes, even a moderate-size earthquake could trigger a larger landslide, but usually a large earthquake, leading to strong, low-frequency ground shaking, would be required to trigger e.g. a large, deep-seated rock avalanche.

The dataset presented in this study is the first of its kind for Norway, but it is expected to be highly incomplete for several reasons. Most of the most landslide-prone areas in Norway are remote, and many small rockfalls and landslides go unnoticed. It is therefore very likely that EQIL will not be identified, or that they will be noticed long after the earthquake and therefore not identified as an EQIL. A further limitation is that much of the data considered here is from macroseismic questionnaires, where landslide observations are not specifically asked for. It is thus possible that landslides have been observed in connection with an earthquake but not reported because the respondent did not find the information relevant. Systematic investigation of remote sensing data before and after large earthquakes may allow for a more systematic mapping

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of EQIL in future studies. Such an approach may also allow for mapping EQIL triggered by earthquakes with smaller magnitudes than considered in this study.

## 5 Conclusions

In this study we have identified 22 earthquake-induced landslides (EQIL) that have been triggered by 8 Norwegian earthquakes of M≥4.5 in the period 1800-2021 CE. Reports of the EQIL are found in macroseismic reports and in the Norwegian Landslide Database. The events are mostly rockfalls, as well as a few clay slides, and they are distributed over large areas of northern and southern Norway.

The maximum EQIL distance limits and landslide affected areas are consistent with observations from other intraplate areas, and ½ to one order of magnitude larger than those predicted from empirical studies in tectonically active areas. The larger distance and area limits are most likely due to differences in ground motion attenuation, though other factors may influence those limits as well. Slope susceptibility is another important factor in the triggering of EQIL in intraplate areas, and for three of the earthquakes triggering EQIL, precipitation is expected to have increased the susceptibility of the affected slopes before the earthquake.

The EQIL are mostly small events, as one would expect considering the high frequency content and short duration of ground shaking from moderate-magnitude earthquakes. We do not expect Norwegian earthquakes to trigger very large landslides or rock avalanches, and the hazard related to EQIL is thus mostly at a local scale. However, considering the damage potential even of small rockfalls and slides, the potential for EQIL should be incorporated in natural hazard risk management in Norway.

## Appendices

### A Earthquakes with M≥4.5 in or near mainland Norway

**Table A1. Earthquakes with M≥4.5 in the time period 1800-2021 CE within the polygon shown in Fig. 1, extracted from the NNSN earthquake database. Abbreviations: Lat: latitude; Lon: longitude; M: magnitude; type: magnitude type. For events with both $M_L$ and $M_W$ available, the largest is presented. * is magnitude derived from macroseismic data (Mäntyniemi et al., 2020).**

| Time | Lat | Lon | M (type) |
|---|---|---|---|
| 1819/08/31 | 66.40 | 14.40 | 5.9 (*) |
| 1834/08/17 | 61.50 | 4.10 | 4.9 ($M_L$) |

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| | | | |
|---|---|---|---|
| 1834/09/03 | 59.50 | 7.90 | 5.0 ($M_L$) |
| 1841/04/03 | 57.00 | 8.50 | 5.3 ($M_W$) |
| 1851/04/13 | 58.80 | 10.80 | 4.6 ($M_L$) |
| 1865/05/07 | 59.00 | 6.10 | 4.9 ($M_L$) |
| 1866/03/09 | 65.20 | 6.00 | 5.9 ($M_W$) |
| 1871/06/30 | 58.10 | 8.00 | 4.7 ($M_W$) |
| 1879/01/04 | 61.00 | 2.00 | 4.5 ($M_L$) |
| 1880/08/04 | 63.60 | 3.90 | 4.5 ($M_L$) |
| 1886/10/24 | 62.00 | 6.90 | 4.8 ($M_L$) |
| 1892/05/15 | 61.40 | 5.10 | 5.7 ($M_W$) |
| 1894/01/02 | 60.00 | 15.00 | 5.1 ($M_W$) |
| 1894/07/23 | 67.90 | 13.30 | 5.4 ($M_L$) |
| 1894/10/30 | 67.30 | 13.00 | 4.7 ($M_W$) |
| 1895/02/05 | 65.00 | 6.00 | 5.3 ($M_L$) |
| 1899/01/31 | 60.10 | 5.50 | 4.6 ($M_L$) |
| 1901/11/09 | 59.70 | 13.80 | 4.7 ($M_W$) |
| 1902/01/25 | 61.60 | 5.00 | 4.5 ($M_W$) |
| 1902/02/09 | 59.50 | 4.00 | 4.5 ($M_W$) |

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| | | | |
|---|---|---|---|
| 1904/10/23 | 59.20 | 10.50 | 5.4 ($M_L$) |
| 1904/10/30 | 69.70 | 18.90 | 4.7 ($M_W$) |
| 1905/02/06 | 61.50 | 5.10 | 4.5 ($M_L$) |
| 1906/06/03 | 57.60 | 6.20 | 4.5 ($M_L$) |
| 1907/01/10 | 59.60 | 12.30 | 4.7 ($M_W$) |
| 1907/01/14 | 66.60 | 9.50 | 5.0 ($M_L$) |
| 1907/01/27 | 66.20 | 8.60 | 5.2 ($M_W$) |
| 1907/06/29 | 60.50 | 7.80 | 4.5 ($M_W$) |
| 1908/06/30 | 67.20 | 14.60 | 4.6 ($M_L$) |
| 1911/08/24 | 60.00 | 5.90 | 4.9 ($M_W$) |
| 1913/07/19 | 64.30 | 6.30 | 5.0 ($M_L$) |
| 1913/08/04 | 61.30 | 5.20 | 5.2 ($M_W$) |
| 1913/09/11 | 68.30 | 13.20 | 5.0 ($M_W$) |
| 1918/04/10 | 61.50 | 5.90 | 4.8 ($M_L$) |
| 1920/09/06 | 67.10 | 13.90 | 4.5 ($M_W$) |
| 1927/01/24 | 59.90 | 1.80 | 5.7 ($M_W$) |
| 1929/05/23 | 57.20 | 6.60 | 4.9 ($M_W$) |
| 1929/05/29 | 57.30 | 6.40 | 4.7 ($M_W$) |

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| | | | |
|---|---|---|---|
| 1935/07/17 | 65.90 | 7.20 | 5.0 ($M_W$) |
| 1938/03/11 | 61.60 | 4.10 | 5.0 ($M_W$) |
| 1939/10/09 | 58.30 | 8.40 | 4.6 ($M_W$) |
| 1942/11/26 | 59.90 | 6.20 | 4.8 ($M_W$) |
| 1943/08/29 | 58.90 | 5.90 | 4.5 ($M_L$) |
| 1954/07/07 | 59.70 | 4.90 | 4.9 ($M_L$) |
| 1954/07/07 | 59.70 | 5.10 | 4.9 ($M_L$) |
| 1955/04/03 | 62.30 | 5.40 | 4.8 ($M_W$) |
| 1955/06/03 | 61.90 | 4.10 | 5.2 ($M_L$) |
| 1957/06/22 | 68.80 | 14.30 | 4.5 ($M_L$) |
| 1958/01/23 | 65.20 | 6.50 | 5.5 ($M_W$) |
| 1958/08/06 | 59.60 | 5.80 | 5.4 ($M_W$) |
| 1958/12/19 | 66.20 | 13.50 | 4.8 ($M_W$) |
| 1958/12/19 | 66.36 | 13.20 | 4.5 ($M_W$) |
| 1961/04/04 | 61.80 | 1.50 | 5.1 ($M_W$) |
| 1962/10/18 | 60.90 | 11.50 | 4.7 ($M_W$) |
| 1962/12/15 | 66.70 | 13.90 | 5.0 ($M_W$) |
| 1966/09/04 | 62.80 | 6.00 | 4.7 ($M_W$) |

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| | | | |
|---|---|---|---|
| 1967/08/21 | 57.30 | 4.70 | 5.2 ($M_W$) |
| 1968/10/07 | 61.40 | 4.00 | 4.7 ($M_W$) |
| 1971/08/28 | 61.66 | 4.73 | 4.8 ($M_L$) |
| 1974/04/28 | 68.80 | 16.20 | 4.9 ($M_W$) |
| 1975/11/12 | 57.20 | 7.80 | 4.7 ($M_W$) |
| 1976/10/09 | 67.60 | 15.80 | 4.8 ($M_W$) |
| 1977/04/06 | 61.70 | 2.30 | 4.6 ($M_L$) |
| 1977/05/02 | 61.13 | 3.32 | 4.5 ($M_W$) |
| 1977/11/09 | 63.17 | 1.93 | 4.7 ($M_L$) |
| 1978/09/19 | 62.34 | 1.50 | 4.7 ($M_W$) |
| 1980/06/08 | 60.85 | 3.59 | 4.5 ($M_L$) |
| 1981/09/03 | 69.62 | 13.68 | 4.6 ($M_L$) |
| 1982/07/29 | 60.25 | 2.09 | 5.0 ($M_L$) |
| 1983/03/08 | 59.66 | 5.23 | 4.7 ($M_L$) |
| 1986/02/05 | 62.67 | 4.41 | 4.7 ($M_L$) |
| 1986/10/26 | 61.66 | 3.34 | 4.5 ($M_L$) |
| 1988/08/08 | 63.66 | 2.42 | 5.3 ($M_L$) |
| 1989/01/23 | 61.866 | 4.409 | 5.2 ($M_L$) |

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| | | | |
|---|---|---|---|
| 2000/08/12 | 59.748 | 5.329 | 4.5 ($M_L$) |
| 2007/01/07 | 61.991 | 1.119 | 4.8 ($M_W$) |
| 2014/09/15 | 61.662 | 14.194 | 4.7 ($M_W$) |
| 2017/06/30 | 58.986 | 1.773 | 4.7 ($M_L$) |

**Data availability**

Earthquake data used in this study are from the NNSN. The earthquake catalogue with event information is available through https://nnsn.geo.uib.no/nnsn/#/data/events/search. Waveform data can be downloaded through the EIDA system from https://eida.geo.uib.no/webdc3/. The macroseismic archive at UiB can be accessed by contacting the lead author of this study, a scanned version of the SEA is available through https://www.geo.uib.no/seismo/REPORTS/Scandinavian_earthquake_archive/.

The Norwegian Landslide Database is published and maintained by NVE and can be accessed through their map services: https://nve.no/map-services/.

Precipitation data used in this study can be downloaded through the Norwegian Centre for Climate Services webservice: www.seklima.met.no.

**Author contribution**

MBS designed the study with contributions from TH and AN. MBS and TH performed the data analysis and interpretation, all authors discussed the results. MBS wrote the manuscript in consultation with TH and AN.

**Competing interests**

The authors declare that they have no conflict of interest.

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