A re-assessment of the 31st of August 1819 Lurøy earthquake – Not the largest in NW Europe

Eystein S. Husebye & Tarek Rashad M. Kebeasy

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The Lurøy earthquake of the 31st of August 1819, with magnitude MS = 5.8 – 6.2, is claimed to be the largest in Norway and NW Europe in 'historic' times. We present a re-evaluation of the macroseismic observations that reduces its magnitude to MS = 5.1 or equivalently ML = 4.8. We put less emphasis on local secondary effects like avalanches, high sea waves, and mudslides, as they may have been influenced by great amounts of rain reported for August 1819. Important observations for our interpretation are the minimal damage to man-made structures and similarity to the macroseismic observations of the Bodø earthquake of the 15th of December 1962 with magnitude ML = 4.5. A contradiction in a seismological context is that the Lurøy earthquake was allegedly reported felt in Stockholm (> 800 km away) but not in many communities less that 100 km away. Our magnitude estimate will have significance for the risk levels and hazard parameters such as recurrence intervals for large and possibly destructive earthquakes, particularly for offshore north Norway.

Eystein S. Husebye, Department of Earth Science, Allégten 41, University of Bergen, N-5007 Bergen, Norway. E-mail: Eystein.Husebye@geo.uib.no. Tarek Rashad M. Kebeasy, now at National Research Institute of Astronomy and Geophysics, Helwan, Cairo, Egypt.

Introduction

An interesting feature of many earthquake catalogues in aseismic regions is that the largest known events (ML=6+) took place in historical and pre-instrumental times, which for NW Europe is the period 1500-1900. Norway is no exception in this regard as the presumed largest earthquake occurred on the 31st of August 1819 in Lurøy, North Norway with magnitude MS = 5.8 – 6.2 (Muir Wood & Woo 1987; Muir Wood 1989). It is also considered to be the largest in NW Europe and will, as such, serve as a yardstick in seismic hazard analysis, particularly for North Norway and adjacent oil-rich offshore areas (Grünthal et al. 1999).

The problem addressed in this paper is whether the Lurøy earthquake was really the largest in Norway and NW Europe based on available macroseismic information. This study may also be considered as a follow-up to that of Almhjell et al. (2001) who claimed that a more realistic magnitude for the Lurøy earthquake is ML = 4.8. These high-school students were participants in the national young scientists competition with their analysis of macroseismic observations under our Seis-School/Norway project (http://pcg1.ifjf.uib.no/).

Historical seismicity - analysis of macroseismic information

Historical seismicity is derived from macroseismic observations, which relate to how an earthquake is felt by people and possible damage to man-made structures and the environment. In the latter case the most common effects are surface faulting and triggering of avalanches and landslides. More recently, the concept of paleoseismicity has been introduced where the basic idea is that excavations in the field may provide new evidence of past faulting due to large earthquakes (Lagerbäck 1990; Anonymous 2001). Local examples are the many post-glacial (neotectonic) faults in N. Fennoscandia, some of which are thought to be caused by magnitude 8 earthquakes (Lagerbäck 1990; Olesen et al. 1999). Macroseismic intensities are measured on the 12-step MMI scale (Modified Mercalli Intensity) commonly used in Norway. Note that the MMI-scale is in turn derived from the Mercalli-Cancani-Sieberg Scale (MCS-scale) commonly used in Europe. The latter is now replaced by the EMS-98 (European Macroseismic Scale - Grünthal et al. 1998). For historical earthquakes the choice of scale is not critical because there are few details about building codes, constuction of houses and soil responses. To ensure that earthquake catalogues are homogeneous it is necessary to equate intensity observations to an earthquake magnitude. The radius of the

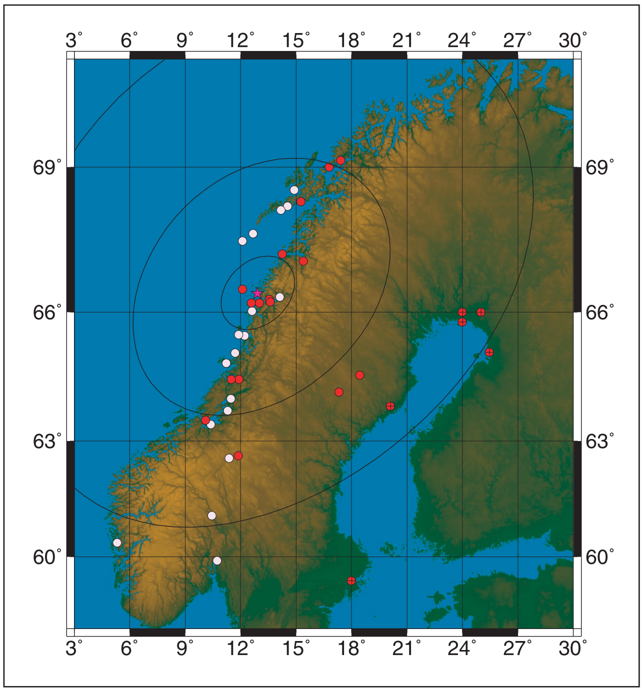

Fig. 1. The Lurøy earthquake of the 31st of August 1819 - epicentre marked by a star. Locations from which reports are obtained, and alternatively lacking, are marked by red dots and open circles, respectively, while suspicious information is marked by red dots with a cross in the middle – details are in Table 1. Note, today questionnaires about earthquakes are sent to the same locations. The ellipses shown, have the largest radii equal to 100, 350 and 700 km respectively. The minor axes are 3/4 of the major ones. The map illustrates an uneven distribution of the observations in declaring Lurøy the largest earthquake in Norway and NW Europe by Muir Wood and Woo (1987) and others. The given radii are easily used for ML or MS-magnitude calculations (see text).

area in which an earthquake is felt is known to correlate with magnitudes hence the modern 'loglinear' relations between area and magnitude. However, the MMI and similar scales have poor magnitude resolution for small to moderate earthquakes in Scandinavia and maximum intensity observations are no longer used for magnitude estimation (Båth 1979; Sellevoll et al. 1982).

Lurøy 1819 – eye-witness accounts

Eye-witness accounts of this earthquake have been reported earlier (Sommerfeldt 1827; Heltzen 1834; Keilhau 1836; Aasvik 1985; Muir Wood & Woo 1987; Muir Wood 1989). These include observations of a rock avalanche from the Lurøy Mountain, which destroyed nearby grazing land close to the sea. At Utskarpen, a potato field slid into the sea but incredibly appeared again later and then disappeared permanently. Mast-high waves, presumably up to 3 - 4 meters high, were generated in the adjacent fjords. Some small rivers became discoloured. Some people working outdoors had problems standing upright and a few chimneys collapsed. In some places fine sand emerged up from the earth by liquefaction. The earthquake was reportedly felt even in far away Stockholm (> 800 km). Many aftershocks were also felt and this activity continued until 1829. However, none of these later events were reported to have caused either damage or strong shaking of houses in the area.

In general, historic macroseismic observations must be analysed carefully; the data are collected in a non-scientific manner and are commonly fragmentary due to population patterns and slow exchange of information. In Norway most earthquakes like that in Lurøy take place in coastal areas, so offshore observations are lacking and hence epicentre locations are not well constrained. We may gain some insight into this kind of problem by examining more recent earthquakes in the same area.

In Table 1 we have listed both villages and communities (marked with church symbols in local maps) where the Lurøy earthquake was reportedly felt and also where there were no reports. Most of these observations stem from Sommerfeldt (1827), Heltzen (1834) and Keilhau (1836). The former 2 authors were priests (clerics-naturalists) living in Saltdalen and Hemnes respectively while Keilhau was professor in natural sciences at the University of Christiania (now Oslo). Whether the information provided by Sommerfeldt and Heltzen is primary (collected by themselves) or obtained from other sources is not clear, particularly as their accounts were published several years later. Nevertheless, in figures 1 and 2 macroseismic observations are shown for the Lurøy earthquake and the Bodø earthquake of 15th of December 1962 respectively. The epicenter of the latter is approximately 100 km north of Lurøy but the similarity in pattern is obvious with a lack of observations from S. Helgeland.

Damage to man-made structures

Damage to housing has not been reported; at most, a few chimneys and walls collapsed and an old farm shed with a heavy stone roof fell down in Saltdalen. This is generally explained in terms of sturdy wooden houses but even the 5 stone churches within 110 km of the epicentre were undamaged; no cracks and no tolling of church bells were reported. In contrast, the Kattegat earthquake of 1759 caused tolling of church bells in some Jutland cities (Bondesen & Wohlert 1997). There are some recent reports that a man experienced problems whilst walking in Lurøy and likewise 2 horses fell to the ground during the most intense shakings (Aasvik 1985).

The outstanding feature here is that no severe housing damage was reported, particularly as many seismolo-

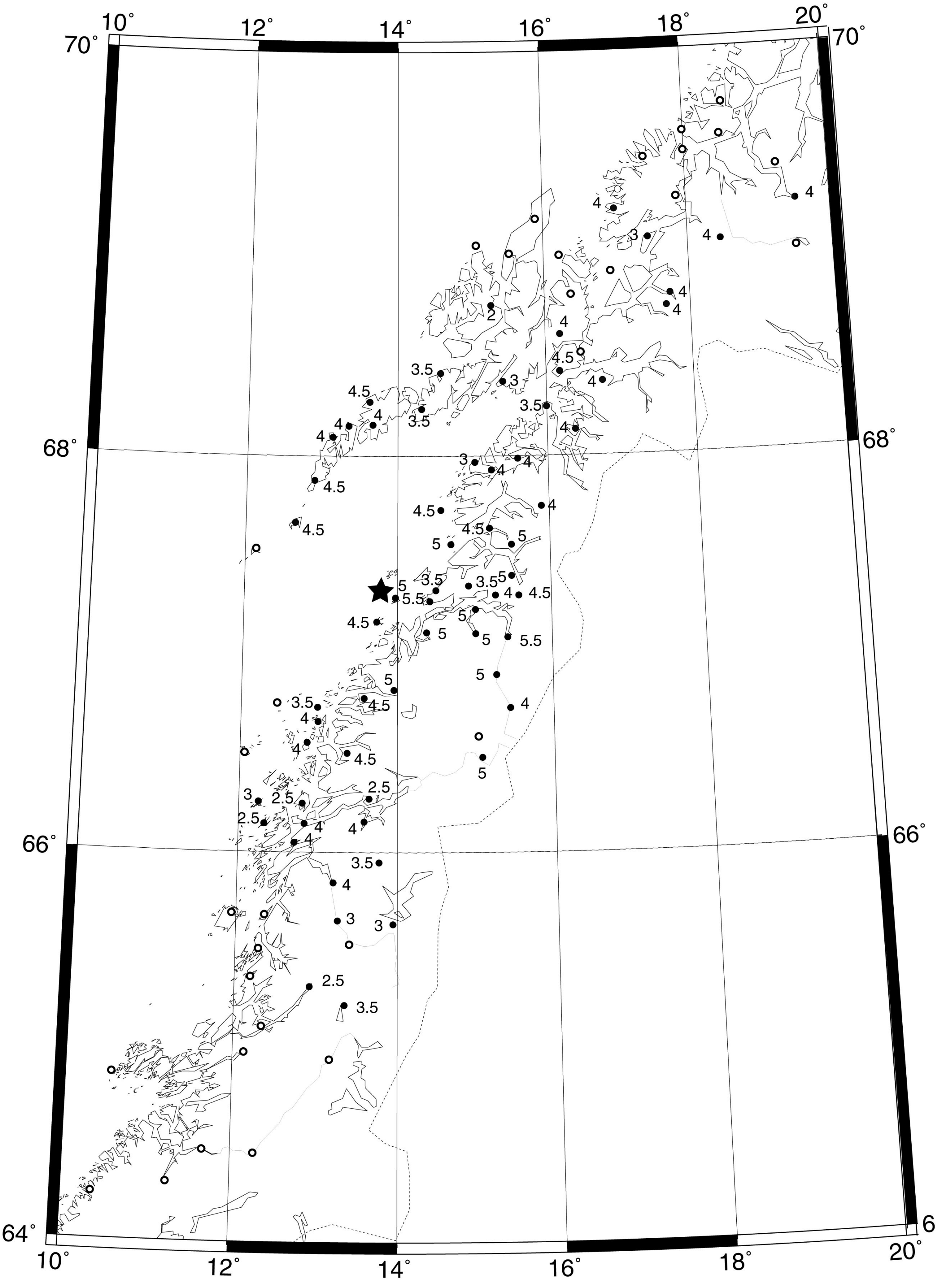

Fig. 2. Map of macroseismic observations for the Bodø earthquake of the 15th of December 1962 - reproduced from Sellevoll et al. (1982). Its Ml-magnitude estimate is 4.5 using the eq (1)-formula. The pattern of the macroseismic observations is similar to that of the Lurøy earthquake except for a shift of ca 100 km northward. Note that reports from the coastal areas of Helgeland are lacking.

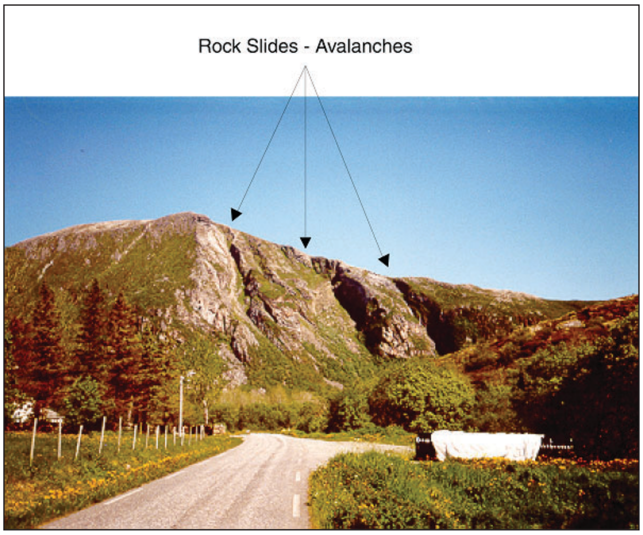

Fig. 3. Photo of Liatinden on Lurøy; the earthquake of 1819 may have triggered the avalanche on the exposed slope without vegetation - that includes also the ravines in shadow. The photo was taken from the south facing due north. It does not show the Liatinden 'wall' facing east where part of the avalanche entered the sea (see photo in Aasvik, 1985).

gists rate the Lurøy earthquake in the magnitude 6 class. On the refined EMS-98 scale, housing is subdivided into classes of structural vulnerability. Timber structures typical of Helgeland some 200 years ago, have a classification matching those of reinforced concrete today so we should not expect much damage but even so the fact that none occurred is unlikely. On the other hand, if the magnitude of the event is around 5 we would not expect damage or that the event should be widely felt more than 150 - 200 km distant. The lack of such reports from S. Helgeland and Lofoten is generally explained in terms of the sparse population and the illiteracy of the local priests and population. We very much doubt statements of this kind as these coastal areas were much trafficked, particularly in spring when hundreds of boats transported fish from the Lofoten winter fisheries to Bergen.

The avalanche in Lurøy

The remains of the Lurøy rock avalanche are shown in figure 3 (a photo taken in June 2001). It appears plausible that the Lurøy earthquake triggered this avalanche but also significant in this context is that August 1819 was a very wet month with continuous rain fall during the preceding 4 weeks. It is also worth mentioning that at the time of writing, January 2002, several landslides related to heavy rains were reported from the Rana area. In fact, most avalanches occur in wet environments, i.e. after persistent rain or in spring as a consequence of snow melting (Ambraseys 1985a). Avalanches were also reported from Hemnes in the Ranafjorden and the small island of Træna to the northwest (Table 1). Also some landslides were reported both from Lurøy and at Utskarpen in nearby Ranafjorden. The latter report is somewhat puzzling as it says that a lost potato field re-emerged after one of the aftershocks and then disappeared permanently. The latter was also attributed to an aftershock (Heltzen 1834). In our opinion the avalanches were primarily related to wet weather conditions. Persistent rain for a period of weeks may have decreased the stability of the exposed rock masses and various kinds of gravel and clay deposits so that additional seismic activity triggered their release much in the same way as explosions in mines trigger snow avalanches (Fedorenko et al. 2002)

Waves in the fjords

From the area mentioned above plus a few other locations there were reports of sudden agitation in the fjords. In extreme cases, waves were mast-high in Ranafjorden. A direct coupling/conversion from seismic P-waves to Rayleigh sea waves does not seem plausible nor did seismic waves cause seiches (standing waves) in Ranafjorden. However, avalanches and mudslides terminating in the sea would cause tidal waves, which may well have been prominent locally. In fact there are several examples in West Norway of tidal waves generated by avalanches; Loen in 1905 and 1936 and Tafjord in 1934. Many people perished in both places when their houses were swept away by tidal waves. While avalanches and tidal waves were impressive manifestations of the Lurøy earthquake, we and others consider it preferable to use distant intensity observations for unbiased magnitude estimation.

Far field intensity

By far field is meant all areas outside the Lurøy-Nesna-Hemnes-Træna area within which avalanches and strong ground shaking were reported (Table 1). A notable exception here is from Rognan (Saltdalen) where the local vicar reported strong shaking of his home. The dining table moved and objects hanging on walls started to swing. However, most surprising is the lack of reports from South Helgeland (roughly between latitudes 65° - 66° N) and hardly any from the Lofoten and Vesterålen areas (Kolderup 1913). The latter have relatively many churches and around 1820 the population totalled 10,000 people. Further south, in Trøndelag (64° - 65° N) there were some isolated reports from obscure places like Overhalla, Statsbygd, Brekken and villages like Levanger, Steinkjer and possibly from the city of Trondheim itself (see Table 1). Among reports from other countries, those from Stockholm appear most genuine. Those from the north part of the Bay of Bothnia area may be confused with local earthquakes while those from Kola (via Paris) are rather unlikely. In a report form central Stockholm quoted by Muir Wood & Woo (1987) we are told that two persons described their experiences as "….a push or shake of enormous nature. A low sound followed by shaking of the house so strong that a tea tray on the wall started to swing and a book in one hand almost fell to the floor. The earthquake lasted 30 to 40 sec ...which later become so noticeable that the tray finally flew 50 cm from the wall. The earthquake was felt on the third floor, but in the lower parts of the house it was hardly noticed". To us, violent shaking on the 3rd floor and hardly any movement below does not seem plausible since a house is an integrated structural unit. Also, the Stockholm report became available mainly after extensive descriptions of the Lurøy event arrived from Oslo after a delay of about 3 months after 31 August. Other peculiarities; why did the adventurer Brooke (1823) only report from Hundholmen (near Bodø) – they travelled across the S. Helgeland coastal areas by boat? Why was a Russian sea captain the only one to report his schooner shuddering? There must have been several such boats with Norwegian crews at Helgeland at the end of August 1819 but there are no reports of earth tremors. And again, why are there no reports from Norway south of central Helgeland, with the exception of some obscure villages? This remains very puzzling as reporters usually supplement their own observations with those of others. Most surprising is that the Lurøy earthquake was allegedly felt in Stockholm but nowhere in S. Norway (south of latitude 63.4° N, except Brekken) or S. Sweden (south of 61° N). In contrast, eastward in N. Sweden, there are several reports from inland communities like Lycksele and from villages in the Bay of Bothnia area which for many years were presumed to refer to a local Swedish or Finnish earthquake (Kjellen 1910; Renquist 1930) but not so by Ambraseys (1985a) and Muir Wood (1989).

Summary of intensity observations

Within a radius of 50 km of the presumed epicentre at Lurøy the quake was apparently very strong and the most significant consequences were avalanches and waves in the local fjords. These avalanches would probably account for most of the reports of mast-high waves that are claimed to have been observed in the fjords. In 1894 an earthquake west of Lofoten apparently sank a Danish schooner, but no exceptional sea waves were reported for this event. Most puzzling is the lack of damage to houses and churches near the epicentre despite claims that the earthquake was felt as far away as Stockholm and Uleåborg (Oulu) in Finland.

In Table 1 we have summarized the origins of both reports (including intensity estimates) and also the absence of reports. In the latter case we intuitively expect that the Lurøy earthquake should have been felt. We have attempted to assign intensity values to these reports despite the fact that secondary phenomena like avalanches and sea waves are not easily quantified in a macroseismic context. Muir Wood & Woo (1987) suggested an overall maximum value of *Io*= VIII for the MS = 5.8 Lurøy earthquake. Perhaps more instructive is a comparison between the Lurøy 1819 intensity observations and those of the relatively recent Bodø earthquake of the 15th of December 1962 (Figs. 1 & 2). For both earthquakes few reports stem from the coastal areas of S. Helgeland, but both were felt eastward to Lycksele in Sweden (Båth 1979) and northward to Vesterålen, Senja etc (Kolderup 1913; Sellevoll et al. 1982). The latter presumably reflect a northward shift of the epicentre of roughly 100 km. The Bodø earthquake observations cannot be explained away in terms of thinly populated areas, poor communications and the inability to report properly if the earthquakes were in fact felt locally.

Re-estimation of the magnitude of the Lurøy earthquake

The obvious advantages of using the perception area for intensity *I* = III as an estimator are that moderate quakes are far more consistently reported than the extreme maxima and that many more observations are available. In the mentioned Almhjell et al. (2001) study, a robust log linear relation between ML-magnitude (tied to Lg surface wave recordings) and area an of perception A_{III} (often ellipse-shaped) was found to be:

$$ML = 0.86 * \mathrm{Log}(A_{III}) + 0.21 \qquad (1)$$

with a correlation factor of 0.77. For an ellipse, $A_{III} = \pi * R_a * R_b$ where R_a and R_b are the major and minor axes respectively, and on average $R_b = 0.75 * R_a$. The above relation was deduced from the analysis of 21 recorded earthquakes in west Norway in the period 1987-2000 using ML-magnitudes from the Fennoscandia earthquake catalogue compiled by the Seismological Observatory in Helsinki. It was also applied to the reported Lurøy intensities and a ML-magnitude of 4.8 was obtained. Based on extensive studies of historical earthquakes in NW Europe, Muir Wood & Woo (1987) derived the following magnitude-intensity relation:

$$MS = 0.69 \log A_{III} + 0.0006 (A_{III})^{1/2} + 0.95 \qquad (2)$$

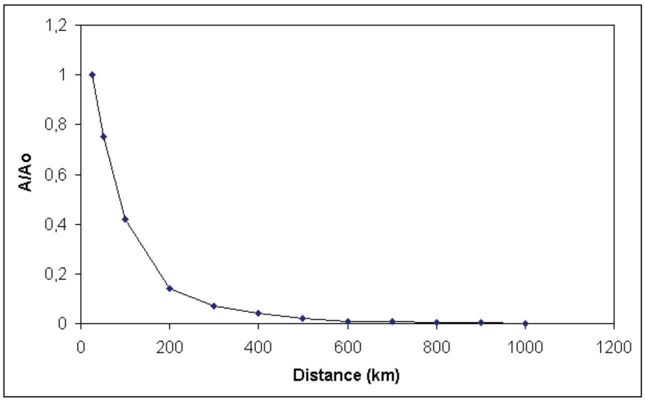

Fig. 4. Relative amplitude decay with epicentre distance. It is calculated from the standard ML-magnitude formula ML = log (A/T) + q (r,f) + C in the frequency band of 2-4 Hz and the amplitude decay term q (r,f) as tabulated in Mendi & Husebye (1994). Notice the rapid decay beyond 100 km away from the epicentre. It does not make sense that the Lurøy earthquake was felt in Stockholm 800 km away and not at many places 100 - 200 km away in S. Helgeland and Lofoten (Fig. 1 & Table 1).

where MS = surface (Rayleigh) wave magnitude. The data set used has a large time span (1903 – 1984) and also embraces a large tectonic but heterogeneous region, 53° to 71° N and 4° to 16° E. The latter is important since human perceptions of ground shaking are tied to high-frequency shear waves with propagation efficiencies that vary significantly across the region (Kennett & Mykkeltveit 1984; Mendi et al. 1997). The most challenging problem in re-assessment of historical earthquakes is the incompleteness of the observational data and the Lurøy earthquake is no exception in this regard. Reports from distant Stockholm, the Bay of Bothnia and Kola are of critical importance as these observations, if genuine, enhance the A_{III} parameter significantly and therefore increase ML and/or MS above plausible estimates. A peculiarity with this particular earthquake is the focus of many investigators on local Lurøy and Ranafjorden descriptions of avalanches and 'mast-high' sea waves that are not taken into account in the methods outlined above for macroseismic magnitude estimation.

There are many magnitude scales currently in use in the Nordic countries (Bungum et al. 1998) but throughout this paper we have only retained that of Almhjell et al. (2001) (ML-magnitude & Eq. (1)) and Muir Wood & Woo (1987) (MS-magnitude & Eq (2)). The similarity of the two scales is the log-linear relation to the area of perception with intensity *I* = III. Note that the differences between various macroseismic scales in the intensity II - V range are miniscule. In the case of the Lurøy earthquake the deletion of extreme intensity observations at Stockholm and the Bay of Bothnia or their reclassification as *I* = II would significantly lower the magnitude of this earthquake. Using the Almhjell et al. (2001) formula with R_a = 700 km and R_a = 350 km the corresponding magnitude estimates become ML = 5.4 and ML = 4.8, respectively. From the formula of Muir wood & Woo (1987) the corresponding magnitude estimates for the same distances are MS = 5.9 and MS = 5.1 respectively. The ML/MS relations are easily calculated from their respective formula. Since the only unknown is the A_{III} parameter, we get

$$ML = 0.72*MS + 1.1 \tag{3}$$

In figure 1, we have drawn the R_a = 350 km contour that encloses reports likely to be of *I* = III reasonably well and in consequence we claim that the ML-magnitude of the Lurøy earthquake was 4.8 or the equivalent MS-magnitude was 5.1. Is there any rational explanation for high intensities and relatively low magnitude for the Lurøy event? There are clearly two potential explanations here or combinations thereof namely i) shallow focus (<10km) and ii) focusing with energy trapping in cone-shaped mountains. Firstly, a shallow focus is intuitively expected as earthquake swarms in Meløy (50 km north of Lurøy) were characterized by shallow foci (3 - 9 km) (Bungum et al. 1979, 1982). Also a recent microearthquake survey in the Ranafjorden showed that most events had shallow foci (Olesen et al. 1999; Hicks et al. 2000). Furthermore, Kebeasy & Husebye (2003a) have demonstrated that the crystalline depression beneath the Nile Valley caused S-waves amplification by a factor of minimum 6 and similar calculations for Lurøy area are underway (Kebeasy et al. 2004). However, the latter calculations are exceptionally difficult due to the sharp topography and the 3D nature of the problem.

Discussion

Why question the MS = 5.8 estimate for the 1819 Lurøy earthquake? In this context the Almhjell et al. (2001) value of ML = 4.8, appears to be incorrect and may be looked upon as amateurish. The latter impression is further strengthened by the fact that the MS = 5.8 estimates stem from comprehensive studies of Fennoscandian seismicity by Ringdal et al. (1982), Ambraseys (1985b), Muir Wood & Woo (1987), Muir Wood (1989) and others. With due respect for these and many other Lurøy earthquake studies, such as the more recent one by Olesen et al. (1999), there appears to be a major flaw in the analysis, namely, the focus on local reports, scant attention being paid to the credence of distant reports upon which the magnitude estimate is based.

Another potent factor here is shallow focal depth (<10 km), which will cause relatively strong shaking locally but with rapidly decreasing intensities with increasing

Table 1. Tabulations of macroseismic information bearing on the Lurøy earthquake (red dots in Fig. 1). Other locations have been added (in particular the Nordland counties, north to Henningsvær and south to Brønnøysund) where this earthquake should have been felt, but where no reports of it exist (open circles in Fig. 1). Also, information that seems unreliable is included. The locations are grouped in terms of direction and epidistance relative to the Lurøy earthquake location given at the top of the table.

Place	Lat. (deg. N)	Long. (deg. E)	Distance (km)	Azimuth (deg.)	Comments
Lurøy	66,41	12,91			Avalanche (VIII)
Near-field					
Nesna	66,20	13,02	24	168	Felt (VI)
Dønnes	66,20	12,58	28	212	Felt (VI)
Utskarpen	66,28	13,56	32	114	Landslide (VI)
Træna	66,50	12,10	37	286	Avalanche (VI)
Hemnesberget	66,22	13,62	38	124	Avalanche (VI)
Sandnessjøen	66,02	12,62	46	197	
Mjølan	66,33	14,13	55	98	
North (N)					
Bodø	67,25	14,25	110	32	Felt (III)
Røst	67,52	12,10	128	344	
Saltdal	67,10	15,40	133	54	Felt (V)
Sørland	67,67	12,68	140	356	
Svolvær	68,23	14,55	214	18	
Selsøya	68,32	15,27	234	24	Felt (III)
Stokmarknes	68,55	14,90	252	19	
Henningsvær	68,15	8,18	280	316	
Senja	69,00	16,80	335	28	Felt (?) (III)
Tranøy	69,13	17,43	357	30	Felt (?) (III)
South (S)					
Brønnøysund	65,47	12,22	109	197	
Vega	65,50	11,90	110	204	
Leka	65,08	11,70	157	201	
Rørvik	64,85	11,23	189	205	
Overhalla	64,47	11,92	221	192	Felt (III)
Namsos	64,47	11,50	225	197	Felt (?)
Steinkjer	64,02	11,47	274	195	Felt (?)
Levanger	63,73	11,30	306	195	Felt (?)
Stadsbygda	63,50	10,10	343	203	Felt (III)
Trondheim	63,40	10,40	352	200	Felt (?)
Far South (FS)					
Brekken	62,63	11,87	422	187	Felt (III)
Røros	62,57	11,38	433	190	
Lillehammer	61,10	10,45	602	192	
Oslo	59,90	10,73	731	190	
Bergen	60,38	5,32	767	213	
Stockholm	59,35	18,00	824	160	Felt(II)
East (E)					
Åsele	64,18	17,32	321	138	Felt (III)
Lycksele	64,57	18,45	327	126	Felt (III)
Umeå	63,84	20,10	440	127	Felt(II)
Arpela	66,00	24,00	499	90	Felt (II ?)
Haparanda	65,78	24,00	503	92	Felt (II ?)
Torneå	66,00	25,00	543	89	Felt (II ?)
Uleåborg	65,10	25,46	589	98	Felt (II ?)

distance from the epicentre. Illustrative in this context is the Meløy micro-earthquake sequence which took place some 45 km further north during a 5 month period in 1978/79 with more than 10,000 recorded. The anguished local population both heard and felt many of these micro-earthquakes. Albeit the maximum magnitude (ML) was 3.2, the estimated maximum MMI intensity *Io* was VI and focal depths were in the 3 - 9 km range (Bungum et al. 1979, 1982). Furthermore, earthquakes in the Lurøy - Ranafjorden area are shallow as mentioned above so there is no need to explain the 1819 macroseismic observations in terms of a MS = 5.8 earthquake.

The Lurøy MS = 5.8 estimate is solely based on the credence given to reports from Stockholm indicating an epicentre distance of 800 km and an intensity rating *I* = III. The trustworthiness of macroseismic reporting is difficult to judge but in the case of statements from Stockholm reporting violent shaking of 3rd floor structures and their absence almost from the 2nd floor do not make sence. We reject Muir Wood's (1989) *I* = III rating city and argue instead, on seismological premises that shaking and house damage were caused by Lg-waves (shear waves trapped in the crustal waveguide). These decay rapidly with distance from the epicentre as shown in figure 4. In other words, Lg-amplitudes are just a few per cent of those in the Lurøy area. Circular shells of radii 300 and 800 km have an area similar to that of Norway and Sweden combined. However, we only have the Stockholm observation to go on. Occasional strong S-wave focusing may take place but not along a purely Baltic shield path. Such phenomenon are observed and modelled for basin areas like the Nile Valley, the Danish and North German basins (Kebeasy & Husebye 2003 a, b) and the North Sea (Mendi et al. 1997).

As shown in Table 1 there have been some reports from the Bay of Bothnia area approximately 500 km away. One event here was rated as a foreshock to the Lurøy earthquake while a later one, presumably on 31st of August 1819, was rated as of local origin by Swedish and Finnish scientists. In an attempt to resolve the contradiction here we asked our colleague Dr. P. Mantyemi, University of Helsinki to check written accounts (newspaper clippings etc.) of this event in the Åbo University library but no convincing evidence was found. Also, the Bay of Bothnia lies within a local Swedish earthquake zone so we concluded that these particular reports do not reflect the Lurøy earthquake at *I* = III level.

One of the referees of this paper suggested that the Lurøy epicentre may have been further west in the Norwegian Sea and also that the report from Kola was correct. However, moving the epicentre westward would increase the Lurøy magnitude and the lack of reports from the Lofoten area would become even more significant. Also, the nomadic Lapp tribes that inhabited Kola at that time were not particularly skilled in scholastic activities.

To summarize the above discussion, we see no strong reason to accept the Stockholm report of an intensity level in excess of *I* = II. Whether these reports were due to local earthquakes or not we cannot say, as historic macroseismic information is not unambiguosly interpretable. Arguing on the basis of Lg-wave propagation characteristics we claim that *I* = III reports from Stockholm and the Bay of Bothnia villages are unlikely when at the same time very many communities in North Norway did not report any shaking locally. Compared to more recent available macroseismic observations, as recovered for the nearby Bodø earthquake of 15th of December 1962, those from the Lurøy event are in good agreement. Hence we claim that the Lurøy earthquake magnitude was around ML = 4.8 or equivalent to MS = 5.1. This result contrasts sharply with the general claim that this earthquake is the strongest that has occurred in NW Europe with a MS magnitude in the range 5.8 - 6.2.

Seismic risk ramifications of the Lurøy earthquake magnitude

Seismicity *per se* and seismic zoning concepts are important in a hazard context. Looking at seismic maps for NW Europe (Grünthal et al. 1999) the seismicity is very dispersed implying relative large epicentre errors. Bungum et al. (2000) give zoning maps for Norway and adjacent areas, which appear overly detailed in view of realistic accuracies of epicentre location. This is obvious for historical data and easily illustrated for the Lurøy earthquake (Table 1). Muir Wood & Woo (1987) located it at 66.4° N; 14.4° E and Ambraseys (1985a) a 100 km further to the east. Even present-day epicentre locations may have errors exceeding 50 km (Husebye et al. 2002).

Evaluation of seismic hazard is always strongly dependent on the presumed maximum earthquake. In the case of North Norway (Helgeland) and adjacent offshore areas, a 25% reduction in risk level results from lowering the magnitude from 6.0 to 5.0 for the presumed strongest earthquake in the region. In particular, the pronounced positive anomaly (0.6 g) offshore (Grünthal et al. 1999; Bungum et al. 2000) would disappear. It is thus far less certain that magnitude 6+ earthquakes might occur as suggested by Olesen et al. (1999). Convincing evidence that ML=6.0 earthquakes occurred in historical times is not strong, as demonstrated above.

The recent discovery of large post-glacial faults (PGF) and landslides in Northern Fennoscandia is generally interpreted in terms of magnitude 7 - 8 earthquakes. In case of PGF's their surface exposure over kilometres is used as diagnostic for the corresponding magnitude estimates. In cases of landslides, Lagerbäck (1990) argues, on the basis of excavations that their release some 8000 - 10000 years ago was also due to such strong earthquakes but no physical modelling was carried out. In fact there are many examples of even low-angle landslides being released without triggering by large earthquakes. Påsse (2001) explains the recent glacial rebound in terms of crustal block adjustments and not in terms of magnitude 7 - 8 earthquakes. Finally, if the Lurøy earthquake magnitude is as we claim around ML = 4.8 the magnitude of other large historical earthquakes may be biased? So far we have investigated the Kattegat earthquake of the 23rd of December 1759 and have reduced the Muir Wood (1989) MS of 5.6 to 5.1. Our tool here was 2D wave field synthetics demonstrating strong shear wave amplification on the flanks of the Danish and N. German sedimentary basins. This in turn affected intensity observations and hence caused a bias in the magnitude estimate (Kebeasy & Husebye 2003b).

Conclusion

In view of the controversy regarding the size of the presumed largest seismic event in Norway, the Lurøy earthquake of the 31st of August 1819, of MS-magnitude of 5.8 and a recent estimate of ML = 4.8 (Almhjell et al. 2001), we have re-examined available macroseismic reports. The many vivid descriptions of avalanches and mast-high waves in local fjords have been given less weight and more emphasis is given to the lack of reports of damage to man-made structures. The magnitude formulas, used by Muir Wood & Woo (1987) and by us, simply depend only on the size of the area of MMI intensity I = III. Using negative evidence (no observations from many local communities) and seismic amplitude reduction with epicentre distance, we conclude that reports from distant Stockholm and the Bay of Bothnia area are, if real, abnormalities and are assigned I = II. Recalculating ML- or MS-magnitudes by excluding outliers/fictitious reports we obtained a Lurøy magnitude of ML = 4.8 (MS = 5.1) which is significantly less than the current value (MS = 5.8 – 6.2) accepted by Muir Wood & Woo (1987) and others. The macroseismic observations for Lurøy are similar to those from the relative recent ML = 4.5 Bodø earthquake of the 15th of December 1962. In terms of seismic hazard this lowers the PGA-estimate by roughly 25 %, removing or reducing the hazard peak off the Helgeland coast (West of Lurøy). Also, the 'forecast' that an earthquake of magnitude 6 or larger may take place (Olesen et al. 1999) becomes far less plausible with the lowering of the size of the 'largest' Norwegian earthquake to around ML = 4.8, which is not unique even for an aseismic region like Fennoscandia.

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