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A Tale of Two Earthquakes in the Gulf of Bothnia, Northern Europe in the 1880s

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Abstract

The earthquakes in the Gulf of Bothnia area on 1 April 1883 and 28 July 1888 are re-investigated using previously disregarded macroseismic observations discovered in contemporary Finnish and Swedish newspapers. Intensity Data Point maps are prepared for the two shocks combining all the available data. The press reports give reason to widen the perceptibility areas and to adjust parameter values for both earthquakes and to remove an erroneous July 1888 entry from the Finnish earthquake catalogue. The improved data samples do not define the perceptibility threshold on the onshore portion of the affected areas, so parameter estimates are based on the assumptions of symmetry of the perceptibility areas and the presence of the largest earthquake effects. The maximum observed intensities are assessed at I_{max} = 5 (European Macroseismic Scale) at a few sites for both earthquakes. The corresponding magnitude estimates are $M_M = 3.7 \pm 0.1$ for the 1883 earthquake and $M_M = 4.1 \pm 0.2$ for the 1888 event. The significance of these earthquakes to the seismicity in the Gulf of Bothnia area is discussed.

Key words: Gulf of Bothnia, Fennoscandia, pre-instrumental seismicity, Intensity Data Point

1. Introduction

The Gulf of Bothnia has long been recognized as one area of enhanced seismicity in Fennoscandia. Even the seismicity maps based on written documentary records stemming from the 1700s show how earthquakes concentrate along its western coast and less numerously so on the eastern side, although, as usual, recent instrumental observations pinpoint especially offshore epicentres more reliably (maps in *Mäntyniemi et al.*, 1993). The area is quite complicated for macroseismic analysis, not only because of the Gulf of Bothnia itself but also because since 1809 it has been crossed by a state border dividing Finland from Sweden. Borders tend to hamper the collection of macroseismic data according to unified procedures and the combination of all available observations (*e.g.*, *Tertulliani et al.*, 1999). It is well grounded to assume that some of the historical earthquakes located on one side of the Gulf of Bothnia in reality occurred offshore but were felt on the coast. Despite the limitations of macroseismic data obtainable in such an environment, studies of pre-instrumental earthquakes are required

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when assessing the seismicity in the Gulf of Bothnia area owing to the insufficient time coverage of the short-period seismograph registration and the rarity of strong shocks during instrumental times. The validity of historical accounts in earthquake studies is discussed by *Hough* (2000), among others, and that of press reports in particular in *Burton et al.* (1984).

This contribution focuses on the earthquakes on 1 April 1883 (EQ#1) and 28 July 1888 (EQ#2) in the area of interest. EQ#1 is listed in the current Finnish earthquake catalogue with the related occurrences between 31 March and 2 April 1883 and EQ#2 in the Swedish catalogue, but several previously ignored felt reports discovered in the contemporary press warrant their reinvestigation. Also, no earlier macroseismic maps exist except an outline of the perceptibility area of EQ#2 (*Kjellén*, 1910). In the following, the data sources are presented and macroseismic intensity is assigned to given places. The values are illustrated as Intensity Data Point (IDP) maps, which represent the formalization of historical earthquake records (*Stucchi et al.*, 2000). The earthquake parameters are estimated and some seismicity features in the Gulf of Bothnia area are discussed.

2. *Macroseismic data*

The earlier literature, original sources and data available for the seismic events of interest are presented in this section.

2.1. *The earthquakes between 31 March and 2 April 1883*

EQ#1 and the related occurrences have been listed in the descriptive earthquake catalogue of *Renqvist* (1930), where entry № 101 is a foreshock at about 10 p.m. local time (LT) on 31 March 1883, № 102 is the mainshock before 10 p.m. LT on 1 April 1883 (EQ#1) and entries № 103 and № 104 are aftershocks on the early hours and in the evening of 2 April 1883, respectively. *Renqvist* (1930) dedicated an ample two pages to the felt reports of these events released in a number of Finnish newspapers. Numerical estimates for earthquake parameters were derived on the basis of his list decades later, but the events have not otherwise been looked into in any detail and no published macroseismic map exists. A search of the Finnish press in 1883 brought to light several previously overlooked narratives from localities mentioned and not mentioned by *Renqvist* (1930); thus, the perceptibility area expanded and the density of observations increased (*cf.* Appendix 1). The discovered reports also provided some additional information on the immediate aftershocks of EQ#1. The relevant contemporary Swedish press was also scanned but no reports were found.

2.2.1. *The earthquake on 28 July 1888*

The earthquake in the Swedish province Ångermanland at about 2 a.m. GMT on 28 July 1888 is listed in the current historical seismicity compilations for Northern Europe. The entry relies on the primary sources described in more detail in *Svedmark*

(1889a,b), *viz.* the Swedish newspapers *Härnösandsposten*, *Östersundsposten* and *Västernorrlands Allehanda* and a letter from Mr E. Waldenström. The press reports originated from a number of places such as Härnösand and Örnsköldsvik along the coast, whereas the letter reported felt observations from the town of Umeå and several villages in its immediate vicinity. A total of 21 places were mentioned (*Kjellén*, 1910, p. 62), all of them located on the coast except Ljungå (Fig. 1). The perceptibility area for EQ#2 outlined by *Kjellén* (1910, p. 115) is essentially a strip along the Swedish coast of the Gulf of Bothnia, since Ljungå was excluded (Fig. 1). Consequently, the epicentral coordinates given in parametric catalogues place EQ#2 onshore in the centre of the strip slightly northeast of the town of Örnsköldsvik (*Wahlström*, 1990).

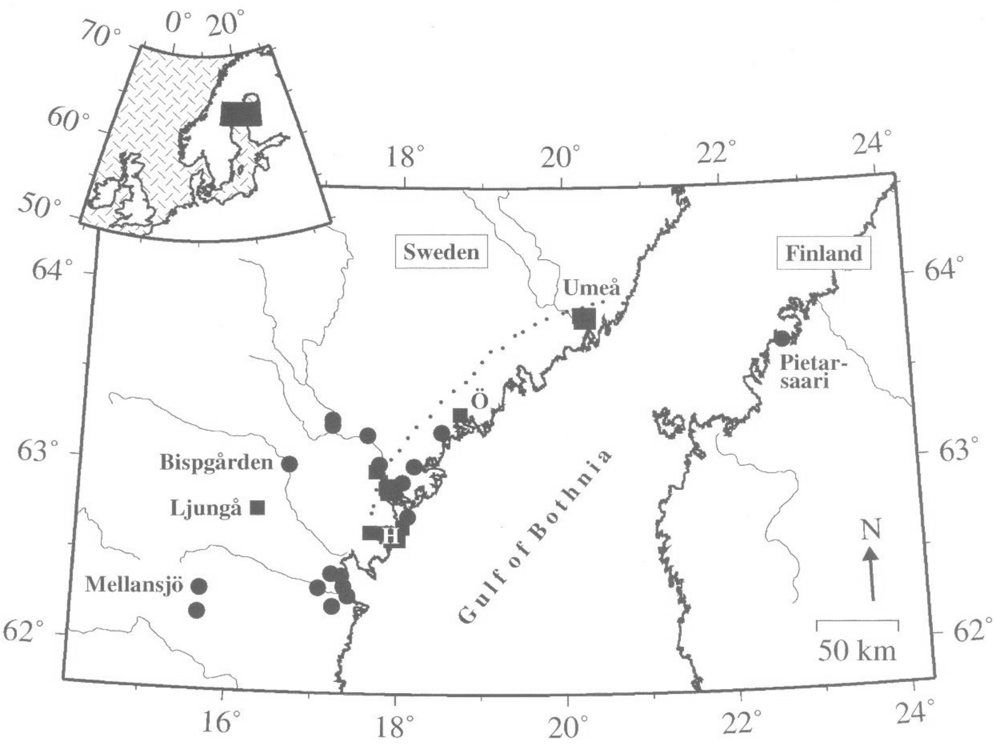

Fig. 1. Felt observations for the earthquake on 28 July 1888 according to the contemporary Swedish and Finnish press. Circles denote sites discovered in the present study, while squares denote those listed by *Svedmark* (1889a,b). A larger symbol is used where several nearby reports have been combined. The dotted line approximates the perceptibility area given by *Kjellén* (1910, p. 115). Letter H (in white) stands for the town of Härnösand and Ö (in black) for the town of Örnsköldsvik on the Swedish coast.

In the present study, previously disregarded reports of EQ#2 were discovered when scanning microfilms of the contemporary Swedish press. *Svedmark* (1889a,b) appears to have taken into consideration only the issues published very shortly after the event, but the flow of related news continued until early August 1888. Besides the three newspapers quoted by *Svedmark* (1889a,b) mentioned above, *Norrlandsposten*, *Norrlänningen*, *Sundsvallsposten* and *Westerbotten* published in Northern Sweden also comprised useful information about the felt effects. These narratives almost doubled the number of Swedish localities (from 21 to 38) where EQ#2 was reportedly felt (Appendix 2, Fig. 1).

In addition to the increased number of place names in the Swedish territory, proof was found that EQ#2 was also felt on the Finnish coast of the Gulf of Bothnia. The newspaper *Vasabladet* reported that a minor earthquake occurred in the town Pietarsaari (Jakobstad in Swedish), Finland and the adjacent archipelago on the early morning of 28 July (Fig. 2). This news remains the only primary source for Finland. It should be noted that the entry № 110 in *Renqvist* (1930) claims on the basis of the same press report that the occurrence took place on 8 July 1888. This is a printing error, so the entry following from the erroneous date should be removed from the parametric catalogues for Northern Europe.

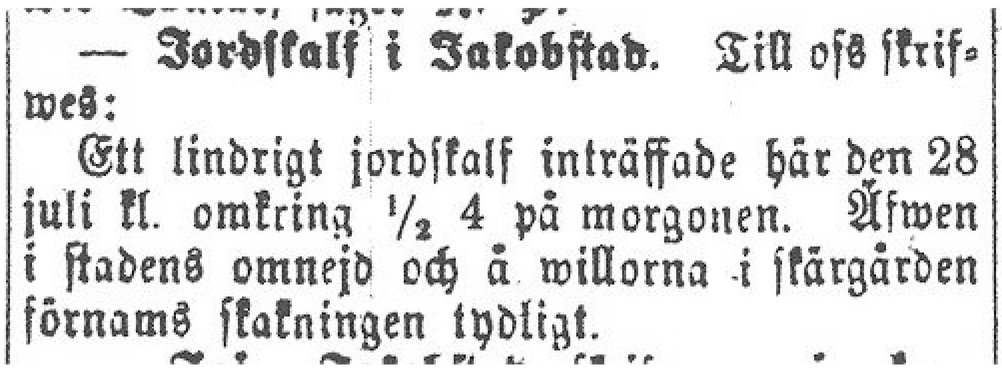
— Jordskalf i Jakobstad. Till oss skrifwes:
Ett lindrigt jordskalf inträffade här den 28 juli kl. omkring ½ 4 på morgonen. Äfwen i stadens omnejd och å willorna i skärgården förnams skakningen tydligt.

Fig. 2. The reporting of the earthquake on 28 July 1888 extracted from the Finnish newspaper *Vasabladet* (4 Aug 1888 № 62 p. 2). This piece of news was quoted erroneously in *Renqvist* (1930, entry № 110), which led to double reporting of the 1888 earthquake in question in the parametric catalogues for Northern Europe.

In Sweden, the spatial distribution of the EQ#2 observations corresponds well to that of the contemporary population, which concentrated especially in the coastal belt and the river valleys, but habitation was also found spread out far inland (*Höijer*, 1965). The density of observations is highest in the province of Västernorrland, where the numbers of inhabitants in each commune were counted in a few tens of thousands, while in Västerbotten towards the north communes had populations of a few thousand, except Umeå (demographic database at *http://www.ddb.umu.se*). It would be credible if earthquake reports had also been obtained from Vaasa, Finland, whose distance from Swedish Umeå is only about 80 km, but such information was not found in the contemporary press.

2.2.2. Were there two separate events on 28 July 1888?

Kjellén (1910, p. 62) presumed that there may have been two seismic events on 28 July 1888. The reasons for leaving Ljungå outside the perceptibility area of EQ#2 were probably its location inland away from the other twenty sites and the respective origin time around 2 a.m. LT. The sources discovered in this study do not support the notion of two events at an hour's interval; instead they confirm that the earthquake at 3 a.m. LT was also felt in Bispgården and Mellansjö not that far from Ljungå (Fig. 1). According to the newspaper *Östersundsposten* (source № 7 in Appendix 2), the earthquake around 2 a.m. was strong enough to make pieces of furniture shake in Ljungå, so it should have been felt in the adjacent areas had it really occurred at that time. *Västernorrlands Allehanda* (№ 10) reported two quakes in the river valley close to Strömnäs and its vicinity, which is here attributed to P and S waves rather than two different shocks.

The two northernmost data points shown in Figure 1 are quite distant from the others, which may suggest another sequence of events. The respective times of observation (LT) were around 3.30 a.m. for Pietarsaari, Finland (source № 9 in Appendix 2) and 3.10 a.m. (№ 11) and 2.30 a.m. (№ 12) for Umeå, Sweden. At that time, both countries had well-established time systems: in Finland the Helsinki local time, in use country-wide since 1862, ran slow of Eastern European Time (GMT+2) by about 20 minutes, while in Sweden the national standard time introduced at the beginning of 1879 deviated by only 14 seconds from the Central European Time (GMT+1). Thus, conversion to GMT yields around 1.50 a.m. for Pietarsaari and 2.10 a.m. and 1.30 a.m. for Umeå, respectively. The first two are considered close enough, but the accuracy of the third can be questioned because the same source also gave the date as 29 July. The majority of the observations were made around 2 a.m. In short, given the attainable time resolution, it is hardly possible to discern other seismicity patterns than one earthquake at around 2 a.m. GMT on 28 July 1888.

3. Intensity assessment

Macroseismic intensity was assigned to the available sites on the European Macroseismic Scale (*Grünthal*, 1998). The intensity assessment is featured in this section.

3.1. The earthquakes between 31 March and 2 April 1883

The felt reports available for EQ#1 and the related occurrences are summarized in Tables 1a and 1b. They range from very short remarks of feeling the ground shaking to more specific descriptions; especially the letters published in a few national papers were a useful source. The most frequently reported indices were a strong or rather strong tremor, rattling of windows and shaking of objects and pieces of furniture. The expression “rooms shook” was interpreted only as perceived ground shaking. Minor damage such as a broken window and tiles falling from a wall was reportedly sustained at a few sites. The assumed direction of movement was often mentioned, but such observations are rather meaningless when made indoors (*Richter*, 1958). An underground roar, often compared to thunder, was also frequently reported, which tells us about the epicentre being relatively close to the observers (*Tosi et al.,* 2000). This may pose a problem, because the roar rather than the ground shaking may be the reason for people awakening or being frightened.

Table 1a. Macroseismic reports available for the earthquake before 10 p.m. local time on 1 April 1883 (EQ#1). The coordinates are given as (longitude °E, latitude °N). № of source refers to Appendix 1.

Place	**Source**	**Classification factors and related remarks**	**Intensity (EMS)**
Alahärmä (22.85,63.25)	22)	Felt.	F
Antiala (22.27,63.12)	15)	The quake was felt and the roar heard.	F
Eisnäs (Vaasa) (21.60,63.11)	26) 28)	Rooms and pieces of furniture shook. Objects moved. In one house pieces of furniture moved from their position.	4-5
Esp[1] (23.05,63.59)	5)	The earthquake was observed.	F
Himanka (23.66,64.06)	19)	Shaking and roar. The tremor was weaker than on 23 June 1882. Rooms shook and windows rattled.	4
Isokyrö (22.33,63.01)	29)	Felt and heard.	F
Jepua (22.63,63.41)	4) 6) 22)	The shock was largely felt.	4
Kauhava (23.07,63.11)	21)	Felt. Weaker than in Pedersöre.	F
Kokkola (23.14,63.83)	9) 17)	Rather strong. Doors closed (?) at some sites and pieces of furniture jumped in their positions; hanging lamps swung considerably, and many buildings shook on their foundations. People walking on the street felt the tremor, but not as strongly as indoors. A sound was heard. The earthquake was rather strong in the countryside as well.	4-5
Kruunupyy (23.03,63.73)	30)	Ground shaking, so strong that walls and ceilings of houses rocked, doors and windows rattled, no damage.	5
Lehmäjoki (22.45,63.06)	15) 21)	Tremor was so strong that all loose objects moved.	4
Lohtaja (23.51,64.03)	24)	A distant roar and ground shaking.	F
Luoto (22.75,63.75)	5) 12)	Houses and beds shook and windows rattled. "It was a really sharp bang."	4-5
Mäkipää (22.24,63.14)	15)	The quake was felt and the roar heard.	F
Monå (22.37,63.39)	15)	A weak ground shaking.	3
Monäs (22.32,63.47)	4)	Ground shaking was reportedly strong, also in other villages in the vicinity.	4-5
Munsala (22.46,63.45)	4) 6) 15)	So strong that the whole building shook, doors clattered and even pieces of furniture moved. A few persons heard a barn creak. In the nearby communes the shaking was also so strong that houses creaked and people heard a shaking movement in the houses. Many outdoors did not notice anything. Houses and doors banged considerably.	4-5
Myllymäki (22.84,63.31)	25)	Some houses and the foundations of one fireplace had been shaken considerably.	4-5
Oravainen (22.38,63.30)	16) 29)	Houses shook on their foundations, a roar accompanied the shaking. Observed in adjacent areas as well.	4
Pedersöre (22.80,63.61)	29)	All the houses and buildings were suddenly shaken. Reportedly stronger than in adjacent areas.	5

Place	Source	Classification factors and related remarks	Intensity (EMS)
Pensala (22.56,63.35)	15)	A person outdoors did not notice anything, while those indoors felt shaking.	4
Pietarsaari (22.70,63.66)	5) 13)	Relatively strong shaking and a roar were observed in the whole town. Windows rattled somewhat. Wave-like motion was felt distinctly on floors. In the tower of the town hall the janitor had to support himself in order not to fall. In one instance tea spilled from a cup onto table, in another a jug and glass clattered together, in a third a window pane broke, etc. Many sleeping people awoke. Reports from the surrounding countryside were obtained. Those asleep were awakened and those awake were frightened by a remarkable, scary thunder-like sound that was accompanied by an earthquake lasting for a few seconds. Those lying down felt the bed shake; houses creaked, pieces of furniture, china and windows rattled.	5
Purmo (22.96,63.14)	5) 14)	A strong roar mistaken for thunder; beds shook in houses.	4
Rekipelto (22.29,63.10)	15)	The tremor was reportedly very strong, stronger than in other nearby villages.	5
Teerijärvi (23.52,63.54)	2)	A loud roar from an earthquake was heard here, and at certain sites of higher altitude windows rattled.	4
Uusikaarle-pyy (22.54,63.52)	7) 8) 10)	A strong earthquake accompanied by an underground roar. It did not last long. Wave-like motion was felt distinctly, objects did not move from their positions. One report: the whole building shook and the lamp on the table as well as the windows rattled. It was observed in the adjacent areas as well and frightened people in places, especially women and children.	4-5
Vaasa (21.60,63.11)	1) 21)26) 27) 28)	Minor ground shaking. Tremor observed at several sites in the town. A few persons ran outdoors along one street. Reportedly strongest at Eisnäs.	4-5
Vanha Vaasa (21.73,63.07)	21)	Felt, mistaken for thunder.	F
Vöyri (22.26,63.13)	3) 4) 6) 29)	Windows rattled in some places and tables and chairs shook in their position; stronger in the northern parts. It lasted for about a minute, and the roar resembled distant thunder. It raised great concern among some people.	4-5
Ylihärmä (22.79,63.14)	18) 22) 23)	A somewhat strong quake in the vicinity of the church. A roar was heard. Stones fell from a wall in one cow stable.	4-5
Ylimarkku (21.46,62.62)	1)	Not felt.	1
Ylivieska (24.56,64.07)	20)	Felt and heard. The rooms shook. It did not last long.	F
Ytterjeppo (22.60,63.43)	11)	Tremor so that houses shook on their foundations. In one house it was very strong. The reporter was in bed in another house and thought the cottage would collapse.	4-5

[1]Name Esp remains unclear. It could refer to Espholmen in Bennäs (Pännäinen in Finnish) in Pedersöre or misspelled Esse (Ähtävä). The general picture of the earthquake having been felt in the countryside surrounding Pietarsaari is not affected by this ambiguity. Espholmen was uninhabited, but there may nevertheless have been observers there at the time of the earthquake. The given coordinates are those of Esse.

Table 1b. Macroseismic reports available for the events on 31 March and 2 April 1883. № of source refers to Appendix 1.

Place	Source	Classification factors and related remarks	Intensity (EMS)
Kruunupyy	30)	At a number of places the phenomenon was noted for the second time between 2 and 3 in the following morning.	F
Pietarsaari	13)	Some people claim that minor ground shaking was felt at about 2 a.m. Others confirm that they also felt a minor tremor on Monday evening. [2 April]	F
Teerijärvi	2)	The roar was heard at many places another time at about midnight. [between 1 and 2 April]	F?
Vaasa	21)	An earthquake was observed at about 10 p.m. 31 March.	F

Only one negative report was available. Intensity values between 3 and 5 were assigned to the other known localities (Fig. 3). The reported damage was considered too occasional and vague to justify intensity level 6. The units of place were villages and small towns. Due to lack of details several places were assigned an intensity range or only a remark "Felt".

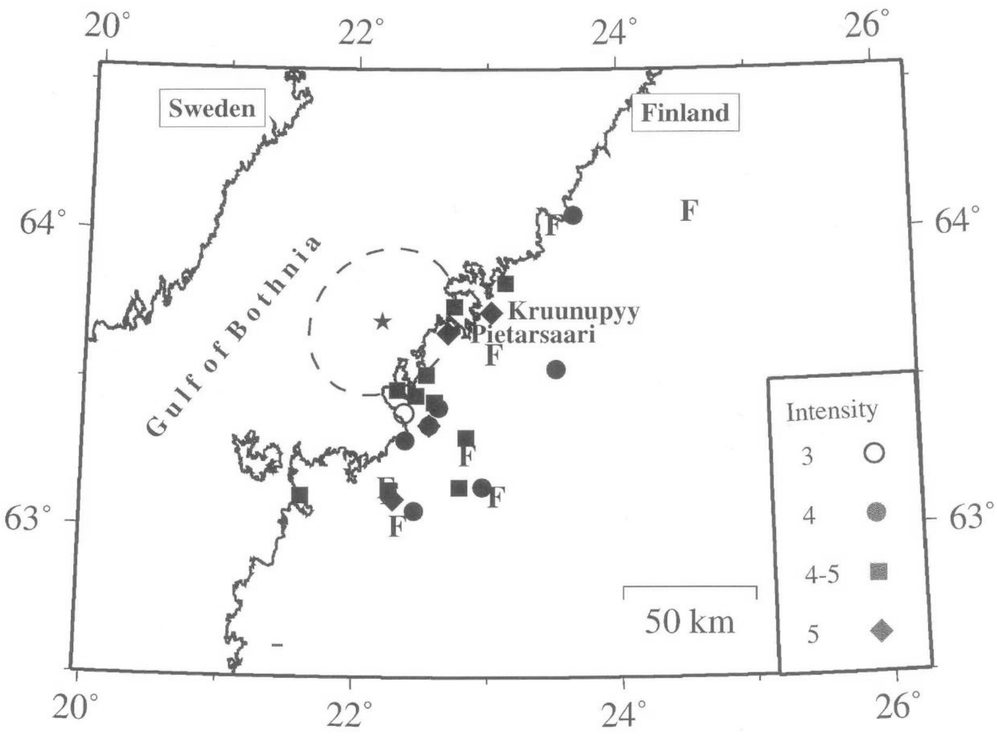

Fig. 3. An Intensity Data Point map for the earthquake in the Gulf of Bothnia on 1 April 1883. Intensity is given on the European Macroseismic Scale. A letter F stands for "Felt" and a minus sign for "Not felt". The star denotes the suggested epicentre and the dashed line an associated error.

3.2. The earthquake on 28 July 1888

The available documentary data comprised no remarks of a weak tremor or anything unusual, which makes sense because EQ#2 occurred at night. The origin time gives the advantage of the relatively objective information about the extent to which people were reportedly awakened by the earthquake, but the drawback of no useful observations made outdoors. The most frequent classification factors were the generality of felt observations, people being awakened, distinct or strong ground shaking and rattling of windows, indicating intensities of 4 and 5. No damage was reported. The concise newspaper reports do not allow a high resolution of intensity evaluation, so most localities were assigned an intensity range of 4-5. However, the reports are quite rational in spite of superfluous information about the assumed duration of shaking and direction of movement and individual usage of terms such as "enormous" to describe the size of the event. Table 2 shows more details of the intensity assessment and Figure 4 the respective IDPs for EQ#2.

Table 2. Macroseismic reports available for the earthquake at about 2 a.m. GMT on 28 July 1888 (EQ#2). The coordinates are given as (longitude °E, latitude °N). № of source refers to Appendix 2.

Place	Source	Classification factors and related remarks	Intensity (EMS)
Bispgården (16.67,63.01)	3)	A shock was felt strongly.	4-5
Bjästa (18.51,63.20)	4)	A rather strong earthquake, preceded by a roar. Houses and furniture shook considerably.	4-5
Björkå (17.61,63.18)	2)	A weak roar accompanied the earthquake, wave-like motion felt, houses shook considerably.	4-5
Forsmo (17.18,63.26)	4)	A strong earthquake made windows rattle in one house. One person who happened to be awake noticed the same shaking in the neighbourhood.	4
Härnön (18.00,62.60)	1)	A strong earthquake woke many persons, pieces of furniture shook, largely observed.	5
Härnösand (17.93,62.63)	7)	Ground shaking and a related roar were observed.	F
Härnösand (17.93,62.63)	10)	A notable earthquake was observed both in the north and south of town [cf. Marieborg].	5
Hemsö (18.11,62.73)	3)	The shock was so strong that a log that had been dragged onshore on a slope moved several cubits [1 cubit = 59.4 cm].	4-5
Lägdom (17.84,62.64)	1)	Many people were awakened and pieces of furniture shook .	5
Ljungå (16.31,62.76)	7)	A strong ground shaking made pieces of furniture shake.	4-5
Lungö (18.05,62.67)	10)	The quake was felt.	F
Marieborg (17.92,62.60)	10)	Ground shaking was strongly felt. Lamps hanging from the ceiling swung, furniture shook etc.	5
Mellansjö (15.66,62.31)	5)	In particular, not far from the railway station many persons awoke, even people more or less hard of hearing. A reporter told that the bed shook in a special way and windows rattled considerably.	4-5
Nyland (17.76,63.02)	2)	The reporter felt a considerable jolt and then shaking, several [light] objects fell from a shelf .	4-5

Place	Source	Classification factors and related remarks	Intensity (EMS)
Ön (17.18,63.23)	4)	Several persons had observed the same shaking [as in Forsmo]. It began with a ground tremor.	4
Örnsköldsvik and its vicinity (18.73,63.30)	7)	Houses shook considerably. A roar was heard as well, resembling distant thunder.	4-5
Pietarsaari (22.70,63.68)	9)	A minor earthquake. The tremor was also felt distinctly in the vicinity of the town and in the villas in the archipelago	4
Ramsjö (15.65,62.18)	5)	A peculiar ground shaking disturbed several persons in their sleep. A minor roar was heard.	4-5
Sandö (17.89,62.89)	1)	The event was felt relatively clearly. Doors opened, objects shook at the sawmill, etc.	4-5
Sandö (17.89,62.89)	10)	A tremor was observed. A strong roar was heard.	F
Sandviken (17.72,62.98)	10)	A tremor was observed. A strong roar was heard.	F
Selånger (17.21,62.41)	6)	The ground shaking was felt distinctly and a roar heard; similar observations also from other places.	4-5
Skarped (17.23,62.23)	4)	Several persons had observed the same shaking [as in Forsmo].	4
Skog (18.04,62.92)	2)	A strong roar woke people. Beds shook and domestic objects and glassware rattled.	4-5
Skönsberg (17.33,62.40)	6)	Windows rattled quite a lot. People awoke and some were frightened.	5
Skottsund (17.41,62.29)	8)	The quake was so strong that houses shook and people awoke.	5
Stigsjö (17.66,62.64)	1)	So strong that windows and doors shook and persons therefore awoke.	5
Stockvik (17.36,62.34)	8)	The quake was so strong that houses shook and people awoke.	5
Strömnäs (17.85,62.89)	10)	The tremor was also observed here. A strong roar accompanied it.	F
Svanö sawmill and nearby hamlets (17.91,62.88)	10)	The tremor was also observed here. A strong roar accompanied it.	F
Tuna (17.06,62.33)	6)	The ground shaking was so strong that clocks on walls stopped.	4-5
Ullånger (18.18,63.01)	2)	A strong earthquake was felt in the town and also on the northern side of the bay. Houses shook.	4-5
Västerhiske (20.20,63.84)	11)	In one house the shaking made a bed jump, the roof or attic seemed to sway from side to side.	4
Umeå town (20.27,63.83), Backen, Böhle, Västerhiske, Grubbe, Grisbacka, Ytterhiske, Teg, Röbäck	12)	A strong earthquake was felt, probably in other places as well, but no information is available. Shaking made beds jump slightly, plates move, windows facing south rattle. Houses seemingly swayed.	4

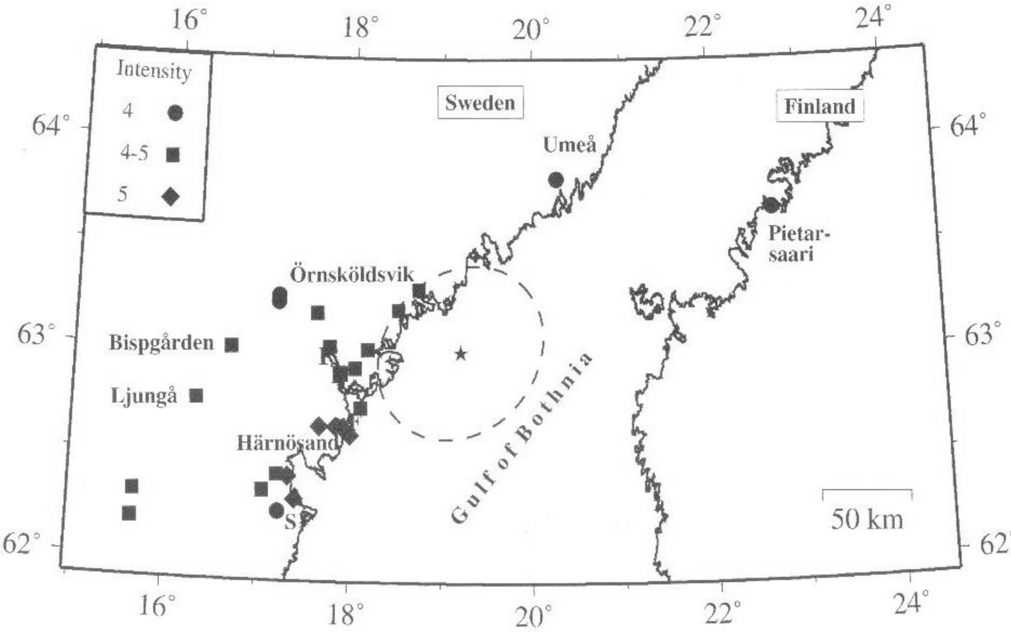

Fig. 4. An Intensity Data Point map for the earthquake in the Gulf of Bothnia on 28 July 1888. Intensity values were assessed on the European Macroseismic Scale. A letter F stands for "Felt". The star denotes the suggested epicentre and the dashed line an associated uncertainty. Letter S denotes place Skottsund.

4. Earthquake parameters

The parameters related directly to the earthquake effects are intensity, its maximum value and perceptibility area, while the macroseismic magnitude and epicentre are the main sequential quantities. *Wahlström and Ahjos* (1984) derived the following relationship for the macroseismic magnitude, M_M, for the Fennoscandian shield:

$$M_M = 0.38 + 1.14 \cdot \log r_F + 0.23 \cdot I_0, \tag{1}$$

where I_0 denotes maximum intensity and r_F the radius of the perceptibility area (km). The relationship (1) is applicable to intensities between 3 and 6-7 (MM or MSK), but it is used in this study because the low intensity values are also similar on the European Macroseismic Scale (EMS). The M_M scale was calibrated with the instrumental local magnitude scale $M_{L(UPP)}$, which is different from that currently in use in Finland (*Uski*, 1997).

Many widely used criteria of macroseismic epicentre determination are related to the perceptibility area. It is obvious from the IDP distributions shown in Figures 3 and 4 that a degree of uncertainty is involved in estimating these quantities. As shown by *Cecić et al.* (1996), a diversity of epicentral solutions can be acquired for coastal areas. Neither the dataset for EQ#1 nor for EQ#2 defines the perceptibility threshold on the onshore portion of the affected areas. The estimates of the perceptibility areas are therefore based on extrapolation and the assumption of symmetry of their shape.

The onshore portion of the perceptibility area of EQ#1 amounts to about 13 300 km^2. This value and the observed maximum intensity I_{max} = 5 (EMS) yield an estimate of the magnitude as M_M = 3.6. If the known portion constitutes 40 to 50 per cent of the total perceptibility area, an estimate M_M = 3.8 is obtained. Thus, the magnitude of EQ#1 is expressed as M_M = 3.7 ± 0.1. In coastal areas the epicentral intensity is often extrapolated from the observed I_{max} value; in this case, however, the maximum intensities are assumed to be found along the Finnish coastline, so the epicentral intensity would not exceed the maximum value utilized here.

The town of Pietarsaari and its vicinity stand out as a potential epicentral area for EQ#1, because it is stated to have experienced strong, if not the strongest, tremor and an aftershock was felt there and in the contiguous Kruunupyy at about 2 a.m. LT on 2 April 1883 (Fig. 3, Table 1b). It is difficult to prove categorically whether EQ#1 was an onshore or offshore event. According to instrumental records, the seismicity is quite modest in the area with few offshore events which confine themselves rather to the Swedish coast of the Gulf of Bothnia (Fig. 5). A slightly offshore location is favoured, because the strongest effects were observed along the coast and the shock was supposedly not felt in Sweden. The epicentre is placed at (22.2ºE, 63.7ºN) with an uncertainty of about 30 km.

Similar reasoning is applied to EQ#2. The area encompassing the available reports comprises much of the sea because of the observation inside the Finnish territory. Its size is assessed at 43 000 km^2, and the maximum observed intensity is I_{max} = 5, which contribute to a value of M_M = 3.9. If this area is increased by at least one third covering lower intensities and the epicentral intensity is extrapolated to I_0 = 6, a magnitude value of M_M = 4.2 is obtained. Thus, the magnitude of EQ#2 is given as M_M = 4.1 ± 0.2. This is only 0.1 magnitude units larger than the value in *Wahlström* (1990) based on a maximum intensity I_{max} = 6 (MM); the increase in the size of the perceptibility area is partly compensated by the lower maximum intensity.

It is hard to discern any area with stronger effects that may hint at the epicentre of EQ#2. The highest intensity values were assessed at Härnösand and Skottsund (Fig. 4), but an epicentre close to these places would require a large magnitude for the event to have been clearly observed in Umeå and Pietarsaari towards the north. Assuming symmetry of the perceptibility area, the epicentre is placed offshore at (19.2ºE, 63.0ºN) with an uncertainty of about 50 km. The probable epicentral area of EQ#2 is almost devoid of any seismic activity during instrumental times. The largest offshore earthquake was of magnitude M_L3.2 and occurred at (18.8ºE, 63.0ºN) on 25 July 1989, not far from the coastline.

The Solberg earthquake of magnitude M_L4.1 that occurred at (17.5°E, 63.8°N) about 100 km from the coastline on 29 September 1983 is the strongest shock in the province of Ångermanland during instrumental times (Fig. 5). Could EQ#2 have occurred in the same area? The perceptibility area of EQ#2 covered exactly the same coastal strip as that of the Solberg event (map in *Kulhánek and Wahlström*, 1985). The main arguments against such a claim are the different intensity values along the coast: those associated with the Solberg earthquake ranged from 1 to 4 (MM) and between 4 and 5 (EMS) in the case of EQ#2. The absence of felt observations from Östersund in 1888 is notable, because it was the publishing town of a newspaper that contained felt reports from the coastal area. The Solberg earthquake was felt in the town of Östersund at the intensity 4 level (Fig. 5). In addition, the observation in the Finnish territory implies that the magnitude of EQ#2 should have been much larger had it occurred that far inland.

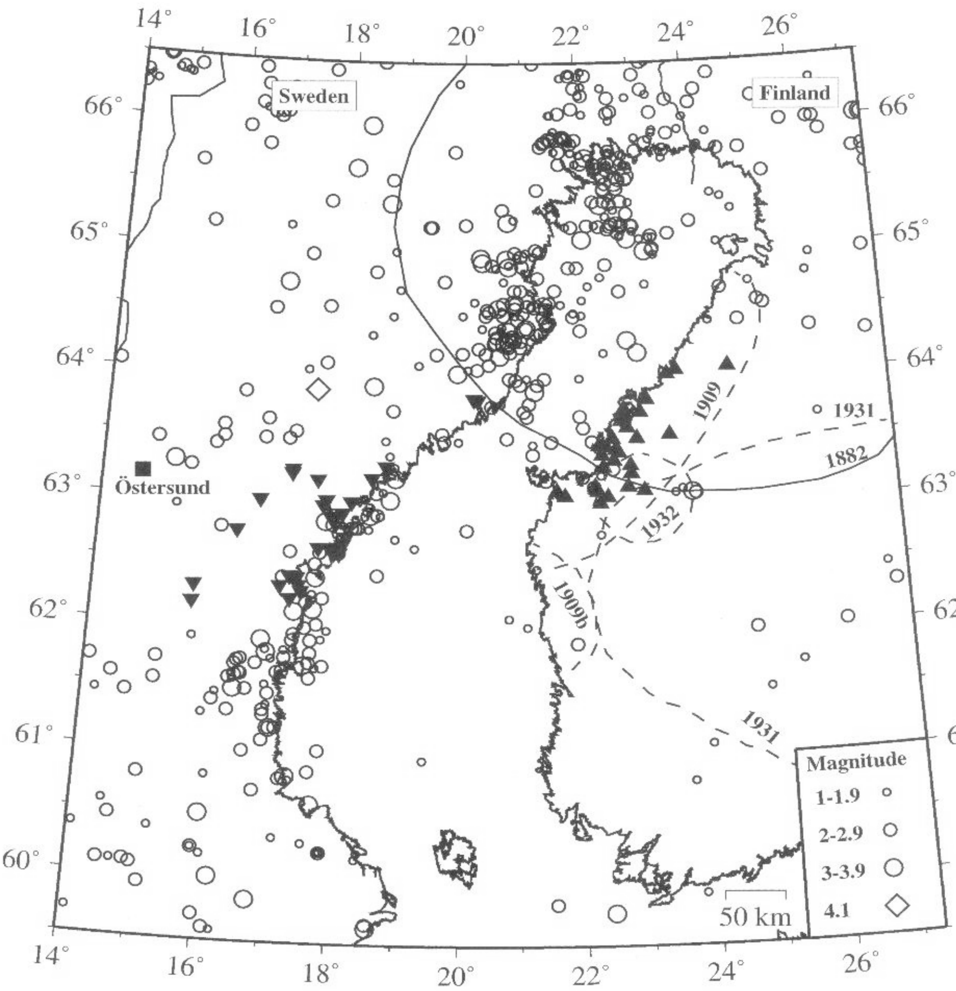

Fig. 5. Earthquakes of $M_L \geq 1$ recorded in the Gulf of Bothnia area between 1965 and 31 May 2005 are denoted by circles. The data were retrieved from *Ahjos and Uski* (1992 and updates on the Internet at http://www.seismo.helsinki.fi). The lowest magnitudes are not complete for the total time period. Only the Solberg earthquake in 1983 exceeded the magnitude $M_L 4$ and is shown by a diamond. The triangles mark the available Intensity Data Points for the earthquake on 1 April 1883 and the inverted triangles those for the earthquake on 28 July 1888. The solid line is an outline of the perceptibility area of the earthquake on 23 June 1882 taken from *Moberg* (1891). The dashed lines are perceptibility areas for the earthquakes on 9 March 1909 (according to *Rosberg*, 1912), 17 to 18 August 1909 [*Renqvist*, 1930; 1909b], 16 November 1931 and 18 March 1932 (*Karjalainen*, 1936).

Related aftershocks would be anticipated given the magnitude of EQ#2, but such information was not found. The spatially and temporally closest known earthquake was felt in Härnösand, Lungö lighthouse and Härnön on 1 June 1888 (*Härnösandsposten* 2

June 1888 № 83 p. 2, *Västernorrlands Allehanda* 4 June 1888 № 84 p. 2). These places are located on the coast, which leaves the exact epicentral coordinates uncertain. However, from the recent instrumental data it is known that several minor events have occurred in the immediate vicinity of Härnösand, so the 1 June 1888 occurrence may have belonged to this group of seismic events.

5. Discussion

In the present study, an extensive search of the contemporary Swedish and Finnish press revealed several previously disregarded first-hand reports of the earthquakes of interest. The discovered sources increased the number of known data points from 19 to 33 for EQ#1 and from 21 to 39 for EQ#2. It is evident that published lists of original sources for historical earthquakes cannot readily be utilized when preparing reliable IDP maps.

Despite the improved samples of macroseismic data at hand, uncertainties associated with the epicentral locations and intensities have to be tolerated in coastal areas. The parameter estimates presented in this study rely on the assumptions of symmetry of the perceptibility area and availability of the strongest earthquake effects onshore. Both requirements are realistic, though, because the most complete macroseismic datasets collected in the Fennoscandian shield are well approximated by circular or elliptic perceptibility areas and it is characteristic of earthquake reports released in the press to gather the extreme observation rather than the average.

The perceptibility area of EQ#1 overlapped that of the large earthquake in the northern Gulf of Bothnia on 23 June 1882 (*Moberg*, 1891), whose magnitude estimate most likely exceeding $M_M4.5$ makes it an eligible candidate for the title of “the largest known Finnish earthquake”. It is therefore of interest if EQ#1 was somehow associated with the 1882 shock.

Conventional aftershock sequences described long ago by *Omori* (1894) are composed of many events gradually diminishing over time, but in this case no seismic activity was observed between the large 1882 event and EQ#1 the following year. The standard measure of determining the sizes of time-space windows for identifying dependent events remains doubtful for the region in question owing to the scarcity of earthquake data. *Mäntyniemi* (1996) tested time windows of different lengths against the Finnish earthquake catalogue for filtering dependent events before applying the Poisson model. The best fit with the model was obtained using a time window of less than a week for a time series spanning from 1957 onwards and containing no magnitudes above M_L4. It is generally assumed that the logarithm of the length of the aftershock sequence increases linearly with the magnitude of the main event, but the time lapse of ¾ of a year between the two events is nevertheless very long for such a small mainshock (on a global scale). Also, EQ#1 was located on the outskirts of the perceptibility area of the 1882 earthquake (Fig. 5) rather than the probable aftershock zone, which is a typical spatial requirement for an ordinary aftershock.

Triggered earthquakes constitute another category of seismic events associated with preceding larger mainshocks. *Hough* (2001) and *Hough et al.* (2003) showed that not only interplate but also intraplate earthquakes may trigger events outside the aftershock zone, or more than 1-2 fault lengths away from the mainshock. In contrast to such long distances, the time windows were quite short, the triggered earthquakes occurring within hours or days after the respective mainshock. This evidence concerned the New Madrid, Central United States, earthquakes in 1811-1812 that may represent the archetype for the largest seismic events expected in intraplate regions (*Hough*, 2004).

Some intriguing comparisons with other Gulf of Bothnia earthquakes can be made. The 9 March 1909 shock of magnitude above M_M4 was widely felt along the coasts (*Rosberg*, 1912). In August 1909 a few minor events occurred on the outskirts of the perceptibility area of the large event of March 1909 (Fig. 5). The earthquake in Central Finland on 16 November 1931 was of similar magnitude and was followed by an aftershock on the same day. A later earthquake away from the epicentral area was observed on 18 March 1932 (classified as an aftershock by *Karjalainen*, 1936), so the temporal and spatial seismicity pattern again bore a resemblance to the 1882-83 case (Fig. 5). Analogous to EQ#1, the delayed, migrated occurrences in 1909 and 1932 were also accompanied by dependent events. It is not possible to test the statistical significance of such seismic behaviour on the basis of only a few examples, but clustering of events catches attention in such low-seismicity areas where several years may pass between felt earthquakes. It is physically meaningful to except causality between earthquakes occurring inside a limited area.

EQ#2 belongs to the largest half a dozen earthquakes in the central Gulf of Bothnia (defined here as covering latitudes 62° – 63.9°N) during historical times (*Ahjos and Uski*, 1992). According to the instrumental records since 1965, the largest event there was the Solberg earthquake of magnitude $M_L4.1$ mentioned above. It is also the only event of a magnitude exceeding M_L4 in forty years. On average, less than two earthquakes of magnitude M_L2 or above occur annually and more than three years are needed for an event of magnitude M_L3 or above in the central part. In terms of the frequency of events, the northern Gulf of Bothnia (covering latitudes 64° – 66°N) shows more seismic activity, because the respective seismicity rates are about four events of magnitude M_L2 or above per year and 1.5 years for magnitude M_L3 or above. However, no earthquake of magnitude M_L4 or above has been registered there during instrumental times so far.

Considering offshore seismicity, the latitude around 63.3°N divides the northern half of the Gulf of Bothnia with a high level of offshore activity from the southern half, where the instrumentally recorded offshore seismicity is very modest. EQ#2 may have occurred offshore, which implies that it was a very rare event with no listed predecessors but, on the other hand, some of the other large historical earthquakes may also have been offshore events. Together with the 1882 activity, EQ#1 and EQ#2 suggest that the seismicity level in the Gulf of Bothnia in the 1880s was quite high in comparison with more recent decades.

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Appendix 1. A list of the primary sources available for the mainshock on 1 April 1883 (EQ#1). The localities mentioned in the report are given in brackets. The sources discovered in this study are marked with an asterisk.

1) *Åbo Underrättelser* 10 May 1883 № 124 p. 2 (Ylimarkku *, Vaasa)
2) *Folkvännen* 12 April 1883 № 83 p. 2-3 (Teerijärvi) *
3) *Folkvännen* 17 April 1883 № 87 p. 1 (Vöyri) *
4) *Folkvännen* 20 Apr 1883 № 90 p. 1-2 (Vaasa, Kokkola and the communes between them, Munsala, Uusikaarlepyy, Monäs, Jepua, Rekipelto, Vöyri) *
5) *Hufvudstadsbladet* 7 April 1883 № 80 p. 2 (Pietarsaari, Luoto, Esp, Purmo)
6) *Hufvudstadsbladet* 13 April 1883 № 85 p. 2 (Munsala, Vöyri, Rekipelto, Uusikaarlepyy, Jepua, Oravainen) *
7) *Morgonbladet* 3 April 1883 № 75 p. 3 (Uusikaarlepyy) *
8) *Morgonbladet* 10 April 1883 № 81 p. 3 (Uusikaarlepyy)
9) *Norra Posten* 5 April 1883 № 14 p. 2 (Kokkola) *
10) *Norra Posten* 5 April 1883 № 14 p. 3 (Uusikaarlepyy)
11) *Norra Posten* 5 April 1883 № 14 p. 3 (Ytterjeppo)
12) *Norra Posten* 12 April 1883 № 15 p. 2 (Luoto) *
13) *Norra Posten* 12 April 1883 № 15 p. 2 (Pietarsaari)
14) *Norra Posten* 12 April 1883 № 15 p. 2 (Purmo) *
15) *Norra Posten* 12 April 1883 № 15 p. 3 (Munsala, Monå, Pensala, Lehmäjoki, Mäkipää, Antiala, Rekipelto) *
16) *Norra Posten* 12 April 1883 № 15 p. 3 (Oravainen) *
17) *Nya Pressen* 7 April 1883 № 93 p. 2 (Kokkola and the surrounding countryside)
18) *Uusi Suometar* 7 April 1883 № 79 p. 2 (Ylihärmä) *
19) *Uusi Suometar* 10 April 1883 № 81 p. 1 (Himanka) *
20) *Uusi Suometar* 17 April 1883 № 87 p. 2 (Ylivieska) *
21) *Vaasan Lehti* 5 April 1883 № 26 p. 2 (Vaasa, Lehmäjoki, Vanha Vaasa)
22) *Vaasan Lehti* 9 April 1883 № 27 p. 2 (Ylihärmä, Alahärmä, Jepua)
23) *Vaasan Lehti* 16 April 1883 № 29 p. 3 (Ylihärmä) *
24) *Vaasan Lehti* 16 April 1883 № 29 p. 2 (Lohtaja) *
25) *Vaasan Lehti* 16 April 1883 № 29 p. 3 (Myllymäki) *
26) *Vasabladet* 4 April 1883 № 27 p. 2 (Eisnäs/ Vaasa)
27) *Vasa Tidning* 3 April 1883 № 26 p. 2 (Vaasa)
28) *Vasa Tidning* 6 April 1883 № 27 p. 3 (Vaasa)
29) *Vasa Tidning* 10 April 1883 № 28 p. 2-3 (Kokkola, Pedersöre, Uusikaarlepyy, Oravainen, Vöyri, Kauhava, Isokyrö, Vaasa)
30) Letter from Kruunupyy district officer to the governor of Vaasa province, dated in Kruunupyy on 5 April 1883 (Kruunupyy)* [source in Finnish: Vaasan maakunta-arkisto, Vaasan lääninhallitus, saapuneet kirjeet II os 1883, Eab:18]

Appendix 2. A list of the primary sources available for the earthquake on 28 July 1888 (EQ#2). The localities mentioned in the report are given in brackets. The sources discovered in this study are marked with an asterisk. The content of the letter (12) was taken from Svedmark (1889a).

1) *Härnösandsposten* 28 July 1888 № 115 p. 2 (Härnösand, Härnön, Lägdom in Säbrå commune, Stigsjö, Sandö)
2) *Härnösandsposten* 30 July 1888 № 116 p. 2 (Björkå, Ullånger and the northern side of Ullånger Bay, Skog, Nyland) *
3) *Härnösandsposten* 1 August 1888 № 117 p. 2 (Hemsö, Bispgården) *
4) *Härnösandsposten* 4 August 1888 № 119 p. 3 (Forsmo village in Ed commune, Ön, Skarped, Bjästa) *
5) *Norrlandsposten* 1 August 1888 № 89 p. 2 and p. 3 (Ramsjö in Northern Helsingland, Mellansjö, in particular the vicinity of the railway station) *
6) *Norrlänningen* 1 Aug 1888 № 60 p. 3 (Skönsberg, Selånger, Tuna) *
7) *Östersundsposten* 31 July 1888 № 60 p. 3 (Ljungå, Örnsköldsvik and its vicinity, Härnösand)
8) *Sundsvallsposten* 1 August 1888 № 119A p. 2 (Skottsund, Stockvik) *
9) *Vasabladet* 4 Aug 1888 № 62 p. 2 (Jakobstad/Pietarsaari) *
10) *Västernorrlands Allehanda* 28 July 1888 № 115 p. 2 (Härnösand town, Marieborg, in the river valley: Strömnäs, Sandviken, Sandö, Svanö sawmill and nearby hamlets; Lungö)
11) *Westerbotten* 30 July 1888 № 54&55 p. 3 (Västerhiske) *
12) Letter from Mr. E. Waldenström, dated in Umeå on 31 July 1888 (Backen, Västerhiske, Grubbe, Grisbacka, Ytterhiske, Umeå town, Böhle, Teg, Röbäck)