Small Publications in Historical Geophysics

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Postglacial Uplift of the Åland Islands, and the World's Oldest Preserved Sea Level Gauge

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1. Introduction

Postglacial rebound plays a fundamental role in the archeology and history of Åland, the autonomous group of islands in the central part of the Baltic Sea. Åland as a whole has emerged from the sea efter the Ice Age; today the highest point is nearly 130 m above sea level. In addition to the main island, Åland consists of 6500 smaller islands and skerries, gradually emerging from the sea. Large parts of Åland are very low, indicating a considerable areal increase in historical time.

We will here study the postglacial uplift of Åland using the many long sea level records from there and the adjacent coasts of Finland and Sweden. The result will be applied to estimate the areal increase during the present millenium. Also, land uplift comparisons will be made with a study based on old maps and with another one based on ancient boulder shores, of which there are very many on Åland. Last but not least we will investigate what seems to be the oldest preserved sea level gauge (tide gauge) in the world, situated on Åland. This will be made utilizing the land uplift results together with old sea level data from other stations in the Baltic.

2. Postglacial uplift from long sea level records and old maps

A consistent computation of the postglacial uplift of the whole of Fennoscandia is presented by Ekman (1996). The basic framework of this computation is the large number of reliable sea level series in the Baltic Sea area spanning 60 years or more, many of them about 100 years. One station, Stockholm, even has a series of 200 years. This station is used as a reference station in the Baltic, by which all other stations there are reduced to a common time span, the 100-year-period 1892 - 1991, in order to eliminate oceanographic changes. The resultant land uplift rates give the apparent uplift, i.e. the uplift relative to sea level, during the period in question.

From the above computation we extract the results of the 14 sea level stations on and surrounding Åland, 2 on Åland, 6 in Finland, and 6 in Sweden; see Table 1 and Figure 1. As is known, however, the sea level undergoes a eustatic rise due to the mild climate during the present century, making these uplift values not representative for earlier centuries. By combining sea level changes at Stockholm and Amsterdam since 1700 (Ekman, 1988; Woodworth, 1990) with climate changes in the northern hemisphere since about 800 A.D. (Hammer et al, 1980; cf. also Warrick & Oerlemans, 1990) we may conclude that the mean eustatic change of sea level during this millenium has been about 1.0 mm/yr smaller, and, accordingly, the apparent land uplift about 1.0 mm/yr larger, than during the present century. Based on Table 1 and this

Table 1. Long-term sea level stations on Åland, in Finland and in Sweden with coordinates, time spans and apparent land uplift rates (u) 1892 - 1991 in mm/yr.

Station	Lat.	Long.	Years	u
Lemström	60 06	20 01	1889 -	4.6
Degerby	60 02	20 23	1924 -	4.1
Helsinki	60 09	24 58	1904 -	2.3
Hanko	59 49	22 58	1888 -	3.0
Turku	60 25	22 06	1922 -	4.0
Lypyrtti	60 36	21 14	1858 - 1922	5.1
Rauma	61 08	21 29	1933 -	5.2
Mäntyluoto	61 36	21 29	1913 -	6.3
Gävle	60 41	17 10	1896 -	5.9
Björn	60 38	17 58	1892 - 1976	6.0
Stockholm	59 19	18 05	1774 -	4.0
Grönskär	59 16	19 02	1849 - 1930	4.0
Södertälje	59 12	17 38	1869 - 1969	3.7
Landsort	58 45	17 52	1887 -	3.1

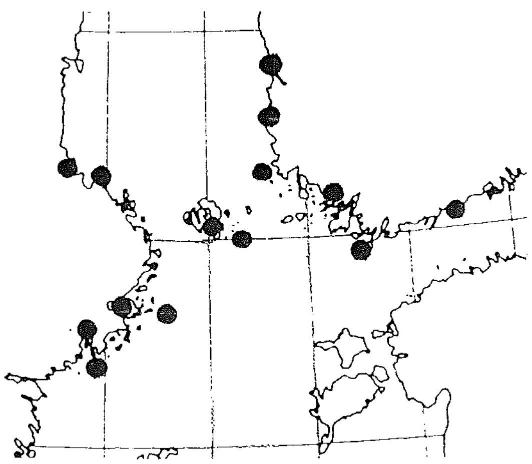

Figure 1. Sea level stations (of Table 1) on and around Åland.

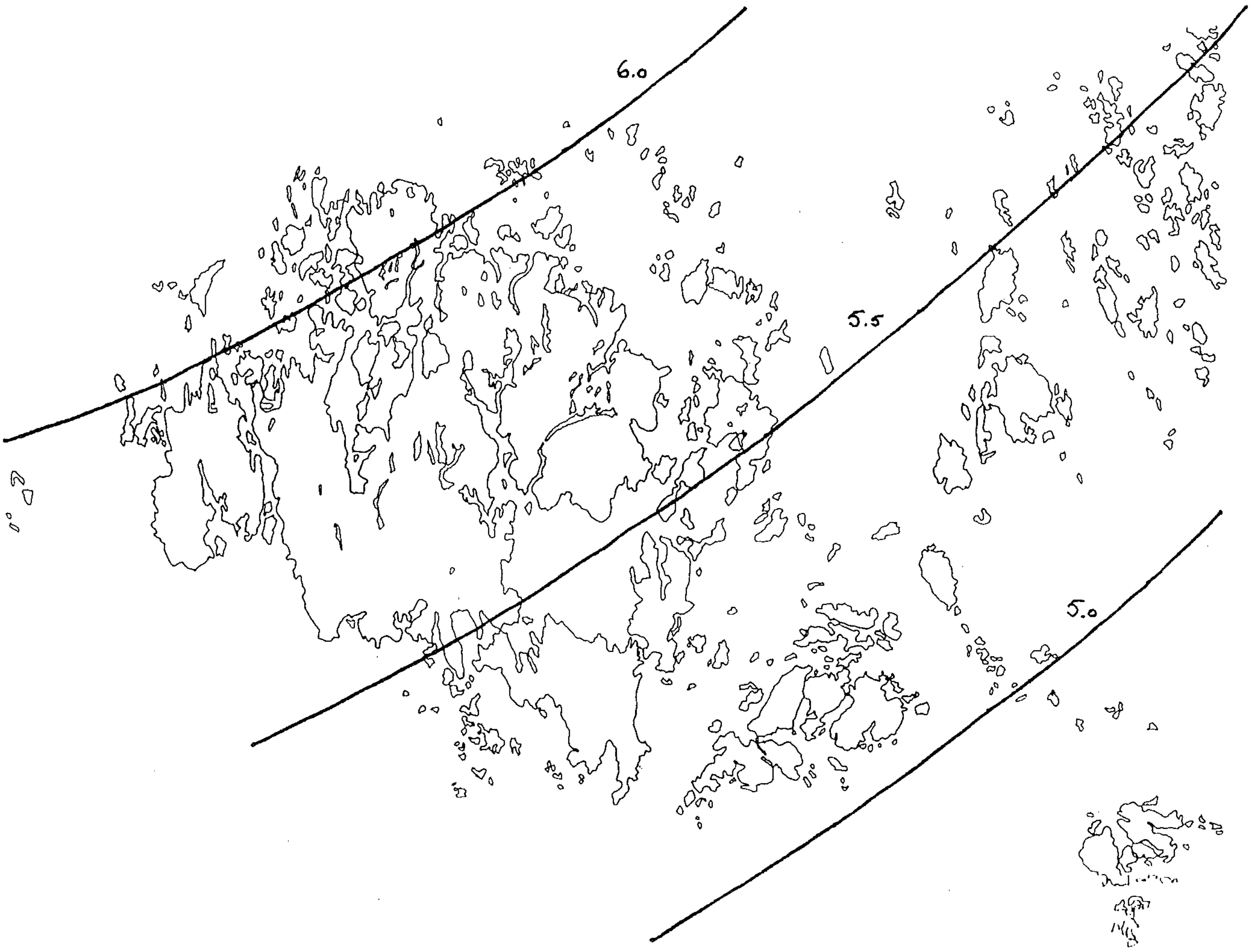

Figure 2. Mean apparent uplift of the Åland Islands during this millenium in mm/yr.

conclusion, Figure 2 shows a map of the mean apparent uplift of the Åland Islands during this millenium. The uplift rates range from 4.8 mm/yr in the south-east to 6.1 mm/yr in the north-west. The standard error in the uplift values may be estimated at 0.4 mm/yr (Ekman, 1993); the standard error in the uplift differences is considerably smaller.

The areal growth of Åland in historical time may now be estimated. Jaatinen et al (1989) have published a curve showing the percentage of Åland situated at different levels. From this it may be inferred that 35 % of Åland is below the 5 m level (in the Finnish height system N 60 with epoch 1960). Thus we are interested in when this level coincided with the sea level. Applying 5.7 mm/yr as the uplift rate for central Åland we find that this occurred about the year 1100, with a standard error of a little more than 50 years. We conclude that during the last 900 years the area of Åland has grown by as much as 50 % (from 1000 to 1500 km^2). It is obvious that this has had a great impact on human living and settlement (cf. Nunez, 1993). In certain flat areas the coast can be shown to have moved more than 5 km during these 900 years.

The topographic circumstances make the Åland landscape in some areas change considerably due to the postglacial uplift even in a few hundred years: New islands are born and later turn into peninsulas, bays are cut off from the sea and turn into lakes etc. These changes can be seen when studying old maps of Åland. There is a wealth of such maps from the 1700s. Åse (1964) has used this to try to estimate the uplift, carefully dealing with possible error sources of the method. The accuracy of this method does not allow any conclusions about uplift differences within Åland but may be useful for estimating an average value of the uplift. Åse has used 21 maps from places spread all over Åland except the outer achipelago, most of them dating from the 1760s (three of them, however, date from the year 1700). The average of his results is 5.7 mm/yr. Adding 1.0/2 = 0.5 mm/yr to compensate for the eustatic rise of sea level during the later half of the period since then, we arrive at 6.2 mm/yr. This figure is in good accordance with the corresponding value from Figure 1, which is 5.7 mm/yr.

3. A comparison with raised boulder shores

There is a very large amount of raised beaches in the form of boulder fields on Åland. Several of them are impressive; the largest ones reach a length of almost 1 km. The higher ones often date from the earliest stage of the Litorina Sea, 5000 - 4500 B.C., which has produced the best shorelines (cf. Donner, 1980) in Fennoscandia. Glückert (1978) has made a comprehensive study of some 40 such boulder fields, identifying synchronous fields on different heights in different parts of Åland. The result is a map showing the uplift during the past 7000 years, ranging from 46 m in the south-east to 59 m in the north-west.

To compare Glückert's map with our own we should add about 7 m of eustatic rise of sea level (Mörner, 1980). (The rise of the geoid may be ignored here, as it is proportional to the uplift itself.) We find an excellent agreement between the two results. The isobases have the same direction, and the increase of land uplift from south-east to north-west across Åland is in both cases close to 25 %. All over Åland there is a constant ratio between the two results (of 11 000 years; cf. Ekman, 1996).

4. The Bomarsund sea level gauge - the oldest preserved one in the world

In the eastern part of the main island of Åland there is an old sea level gauge (tide gauge) that also clearly illustrates the postglacial uplift: It no longer has any contact with the sea water. There does not appear to be anything written about this sea level gauge; since it seems to be the oldest preserved one in the world we will investigate it here. (As there are practically no tides in the Baltic, the conventional term tide gauge will be avoided.)

The sea level gauge is situated at latitude 60°12' and longitude 20°15', in a small cove close to the ruins of the former Russian fortress Bomarsund, see Figure 3. The Bomarsund fortress was erected during the first half of the 19th century but never fully completed; it was planned to be one of the largest fortresses in Europe. However, during the Crimean war British ships and French troops attacked the fortress in 1854 and forced the Russians to leave it; it was then blown up. A historical consequence of this event was the international agreement in Paris 1856 according to which the Åland Islands were declared a demilitarized area, an agreement still in force (to which in 1921 was added another agreement on the neutrality of the islands as well as one on their autonomy).

According to the plans, the Russian Baltic fleet should have its main harbour at Bomarsund; this seems to be the background for establishing a sea level gauge there. The gauge consists of a vertical scale carved directly onto the bed-rock and onto a cut stone put on top of that, see Figure 4. The scale is very accurately made with one line for every inch, one more marked line for every six inches (half a foot), and one long line with numbering for every foot. There are two different numberings, forming a "short scale" and a "long scale", respectively. In addition there is a date carved, 1837 May 31 (Julian calender, corresponding to June 10 in the Gregorian one). This gives rise to some questions to be answered: Does the date mark the establishment of the gauge

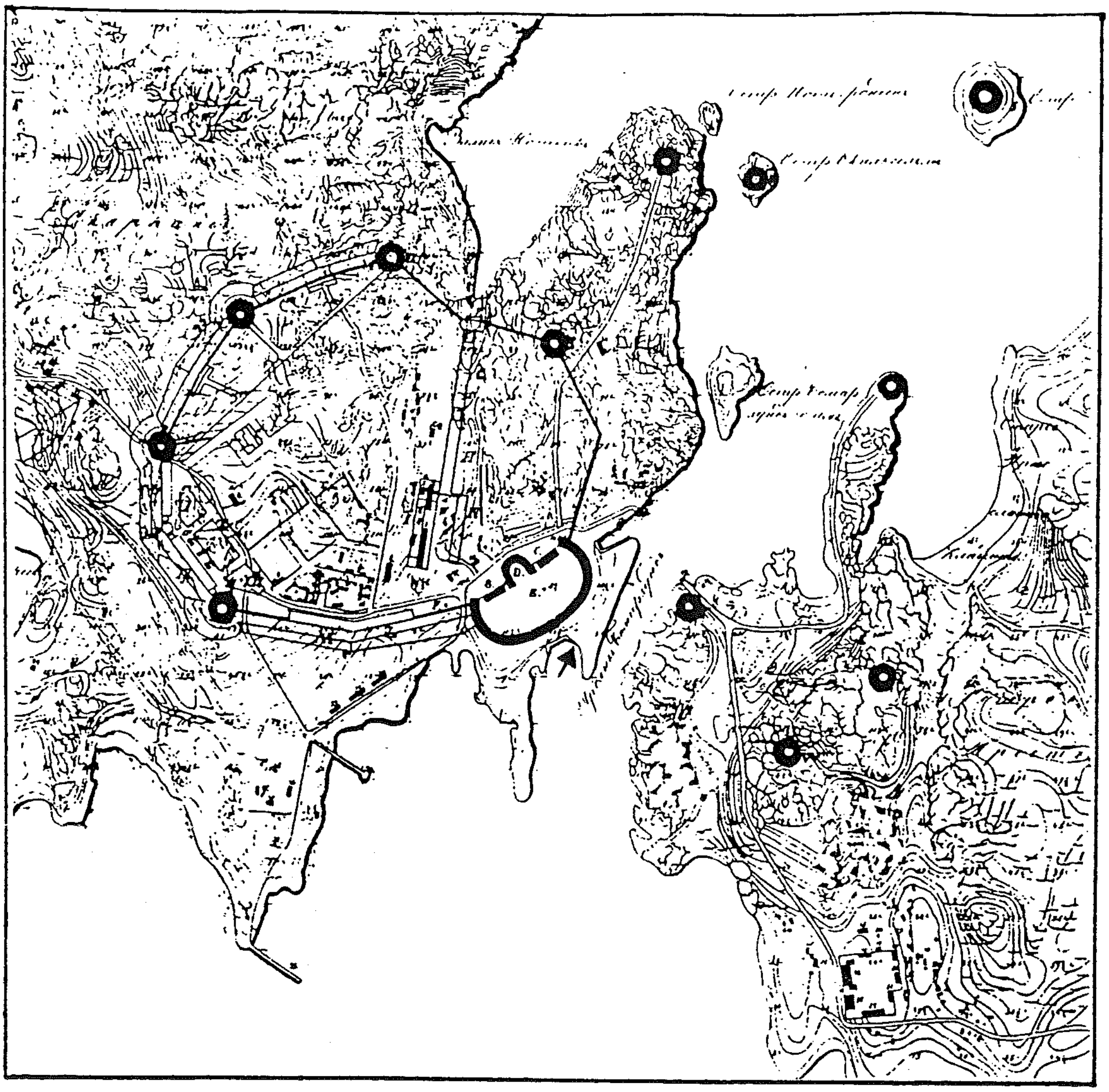

Figure 3. Map of the Bomarsund area with the location of the sea level gauge (arrow).

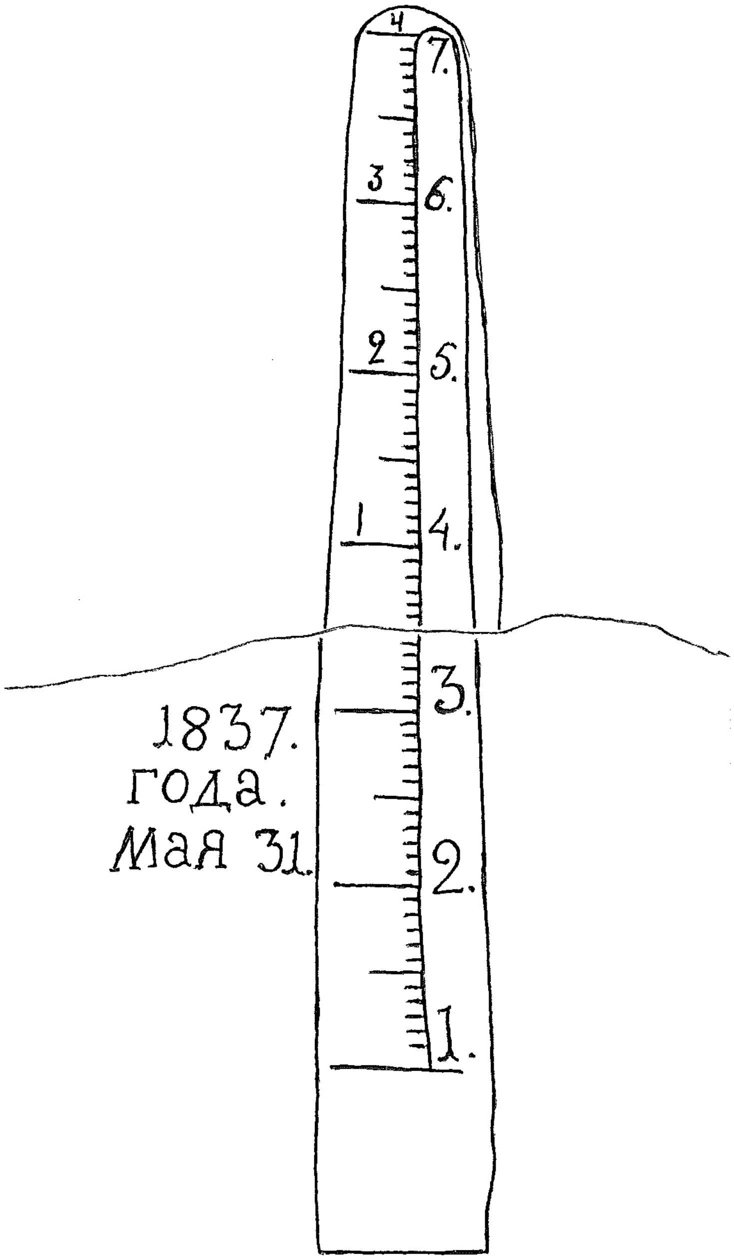

Figure 4. The Bomarsund sea level gauge.

or any other event? Why are there two scales (numberings) and not only one? What was the main purpose of the gauge?

Of the two scales the short one, mainly restricted to the cut stone, seems to range from 0 (or 1/2) to 4 feet, while the long one ranges from 0 to 7 feet, the inch lines, however, from 1 to 7. The scales are numbered upwards in such a way that 4 feet on the short scale corresponds to 7 feet on the long scale. Thus the two scales have their top lines at the same level, the long scale thereby extending further down than the short one. On inspecting the scales closely, it becomes apparent that the date is carved with the same kind of figures as the numbering of the long scale, and thus should be associated with that one. We are led to the assumption that the long scale was made in 1837 and that the short scale was made earlier and later on found too short.

To investigate this closer we make use of the large collection of maps from the planning and construction of the Bomarsund fortress, a complex of structures extending over an area nearly 5 km in diameter. The decision to map the area was made in 1816 (Isaksson, 1981), but for various reasons not immediately implemented. The first accurate maps appeared in 1824 - 1829, forming part of the basis for the decisions in 1825 and 1829 to build the fortress. Further maps were produced now and then during the whole time of planning and erection of the fortress up to its destruction 30 years later.

One of the early maps, of spring 1827, contains a lot of topographic and bathymetric data, showing that both height measurements on land (levellings) and depth measurements at sea (soundings) had been performed; the figures are mostly given with an accuracy of a quarter of a foot. The depth measurements are numerous, more than 200. Thus it seems probable that the short scale part of the gauge was established in the first half of the 1820s as a reference for depth (and height) measurements.

Not very many further important measurements are shown on the maps until autumn 1837, when there appears a map with detailed depth measurements in one of the shallow coves near the main fortress where harbour structures were planned; the figures are mostly given with an accuracy of one inch. This confirms that the date 31 May 1837 of the long scale part of the gauge marks its establishment, and shows that its main purpose, like that of the short scale, was to record the sea level in connection with accurate depth measurements. From this year onwards there are also a lot of accurate height measurements indicated on maps.

An interesting map appears in spring 1842, showing a considerable amount of careful depth measurements made to the south of the main fortress.

They are all made in a grid (Figure 5), indicating that they were performed on the ice-cover of the sea. The number of measurements is no less than 1600, and most of the figures are given with an accuracy of one inch; they are related to "normal sea level". This confirms that there was a need for the long scale as a permanent reference for accurate bathymetric investigations.

At this time there were already some sea level gauges in operation along the coasts of northern Europe, the oldest ones at important sluices (Amsterdam, Stockholm) and the other ones at important harbours. Because of its special construction, with scales cut in stone, the Bomarsund gauge now seems to be the world's oldest sea level gauge still preserved. This makes it worth-while to investigate it further, dealing with the postglacial uplift since then and with the sea level variations of that time.

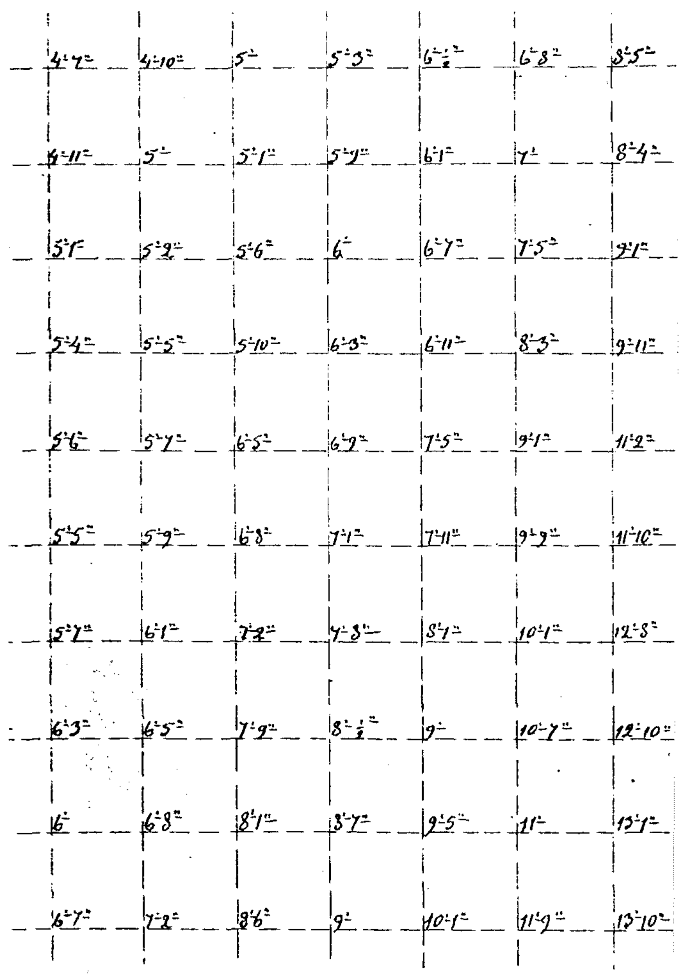

Figure 5. Part of a map of 1842 showing depth measurements in a grid.

5. Postglacial uplift, sea level variations and the Bomarsund gauge

Due to the postglacial land uplift the Bomarsund sea level gauge has risen so much that it no longer keeps in contact with the sea. From Table 1 and Figure 2 we find that the apparent land uplift rate at Bomarsund has been 4.6 mm/yr during the present century and 5.6 mm/yr before that. Thus the land uplift since 1837 can be estimated at close to 80 cm, and since the beginning of the 1820s at nearly 90 cm. At occasions of high sea level in the Baltic (predominantly in autumn) it is still possible to measure the vertical distance of the sea level below the bottom line of the long scale. From such observations at the Bomarsund gauge in autumn 1993 and comparisons with simultaneous data from surrounding sea level stations we can infer that mean sea level nowadays is about 40 cm below the bottom line (0 line) of the long scale and 130 cm below the probable bottom line (the 0 line) of the short scale. These values are also confirmed by levelling (connected to the Finnish height system N 60 on Åland). Consequently, mean sea level around 1837 was about 40 cm above the bottom line of the long scale, whereas it was in the beginning of the 1820s approximately 40 cm below the short scale bottom line. The latter result seems strange.

Let us now discuss the sea level situation at the occasions when the scales were established, starting with the long one of 1837. From the sea level observations at Stockholm (cf. Nordenskiöld, 1858, and Ekman, 1988) we find that this year was a fairly normal one, with monthly means in this region in May and June about 5 cm below mean sea level and in July and August about 5 cm above. Thus the sea level situation fits quite well with the datings in section 4: The long scale was made in May/June 1837, the sea level at that occasion being close to the 1 foot line, preventing the inches to be cut below this level. Soon after that the scale was used in combination with depth measurements during summer, scale readings then being made between the 1 and 2 foot lines.

The short scale from the beginning of the 1820s is more problematic: Was its bottom line really put as much as 40 cm above mean sea level? This is not too far from the normal maximum sea level at the Åland Islands, amounting to 70 cm (Lisitzin, 1957). Unfortunately, the Stockholm sea level series gives no information in this case, since there is a large gap in the series during these years. We have to resort to the sea level series of Swinemünde in the southern Baltic instead (Seibt, 1890; Montag 1964). It indicates that there was a high water year in 1822, with very high sea levels during winter (December 1821 - April 1822); the monthly mean for March reached 30 cm above mean sea level. This picture is confirmed by the two other available monthly mean sea level series from this time, both in the southern Baltic: the short series of København (Simonsen, 1949) and the uncertain one of Kolberg (Anderson, 1897).

Sea level variations within the Baltic are known to be closely correlated; the way they are correlated depends on their duration. Samuelsson & Stigebrandt (1996) show that long-term variations of more than 1 month duration are smallest in the south and largest in the north. Ekman (1996a) finds that the interannual variation as well as the seasonal one at Stockholm and Åland are 1.5 times those at Swinemünde. Therefore, a realistic but uncertain estimate of the monthly mean in March 1822 at Bomarsund is 40 - 50 cm above mean sea level. (A similar situation occurred only a few years ago, in 1990.) This shows that the short scale really could have been established at its high level, provided this occurred in (or around) March 1822 and the depth measurements were made at almost the same time. This, in its turn, requires that the measurements were performed on the ice-cover of the sea, in fact a quite common method for high-accuracy measurements of that time, facilitating the positioning. The sea level readings would then have been made between the 0 and 1 foot lines. Nevertheless, we cannot completely exclude the possibility that the cut stone with the short scale originally was placed somewhere else, which would allow a slightly different year with a lower sea level, and was moved to its present position in 1837.

6. Some final remarks

The Bomarsund gauge, the world's oldest sea level gauge still preserved, was most probably established in winter 1822, and lengthened in summer 1837, with the purpose of being a reference for accurate bathymetric (and topographic) measurements. As other gauges of that time it was not used for scientific studies of sea level changes or land uplift. Studies of the land uplift were still made in the old-fashioned way of making sporadic measurements at approximate mean sea level marks; such marks were cut here first by the Swedes and then by the Russians, obviously not knowing about the Bomarsund gauge. However, the Bomarsund gauge seems to have inspired an Ålander to start measurements for sea level studies: he had a private gauge erected close to Bomarsund in 1851 from which he reported daily sea level observations to the Finnish Society of Sciences during a few years.

Today the Bomarsund gauge would be an excellent one for scientific studies of long-term changes of land and sea because of its unique stability; carved directly onto the Earth's crust it would need no bench-mark control. The only problem is that due to the postglacial land uplift there is no longer any sea water to measure!

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