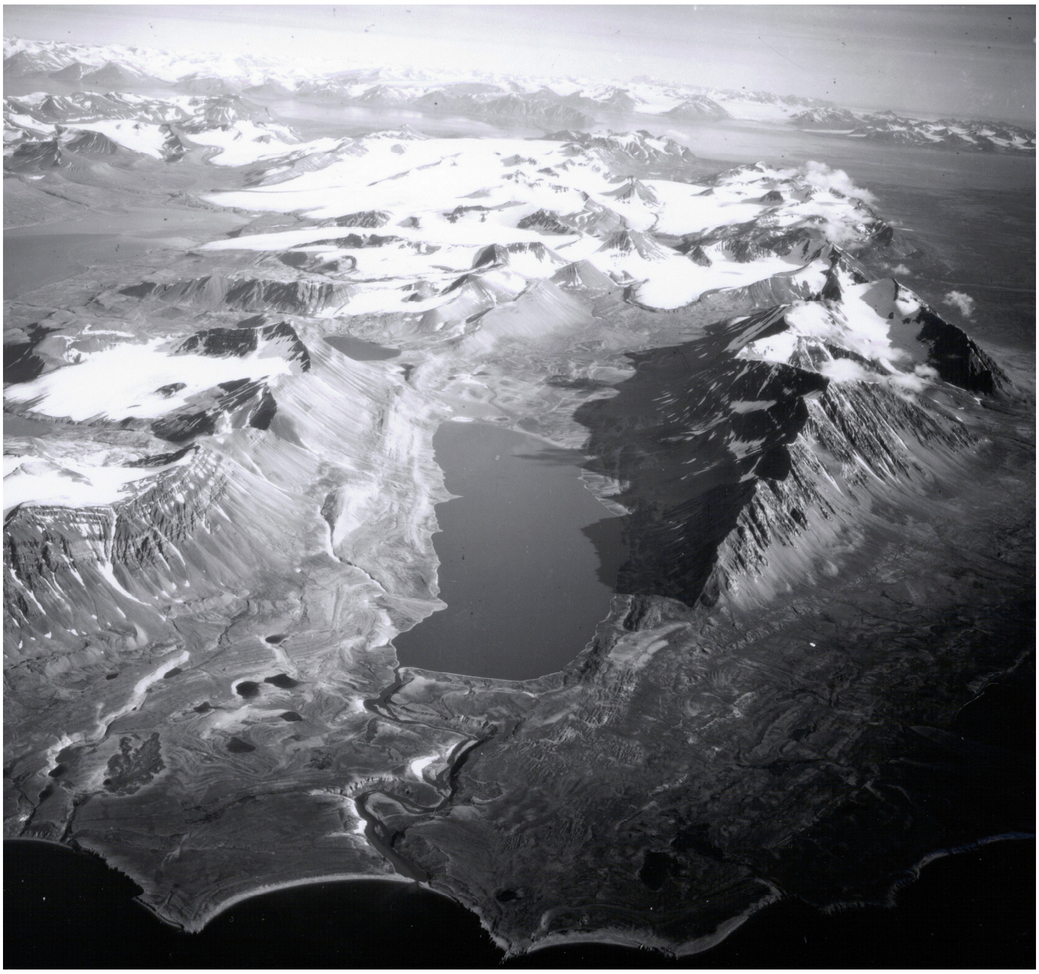
A RECONSTRUCTION OF EQUILIBRIUM LINE ALTITUDES OF THE LITTLE ICE AGE GLACIERS IN LINNÉDALEN, WESTERN SPITSBERGEN, SVALBARD



AG-212

Stephen Bate

University Centre in Svalbard

Autumn 2008

UNIS

A Reconstruction of Equilibrium Line Altitudes of the Little Ice Age Glaciers in Linnédalen, Western Spitsbergen, Svalbard

Stephen Bate
University Centre in Svalbard
Autumn 2008

ABSTRACT

Field altimetry and map based reconstruction techniques are used to hesitantly provide Little Ice Age (LIA) equilibrium line altitudes (ELAs) in eight investigated cirques in Linnédalen, western Spitsbergen, Svalbard. A LIA ELA of *circa* 200 metres (m) above sea level (a.s.l.) to 300 m a.s.l. was found for the valley region. Lower ELAs were found to the north of the study area, suggesting snowdrift ablation and accumulation had a significant impact on the cirques. Furthermore, from comparison with field altimetry measurements and from their small scale, it is advised that serious care has to be taken in using Norsk Polarinstitutt (2008) 1:100,000 maps for ELA reconstruction.

1 INTRODUCTION

1.1 The LIA

The LIA was a widespread climatic cooling event that lasted from approximately the 14th Century to the 19th Century (Grove, 1988; Ogilvie and Jónsson, 2001). In the Northern Hemisphere, a temperature decline from modern normals of between 0.6°C and 2^{o}C was experienced (Mann *et al.*, 1999; Grove, 2004).

The Svalbard archipelago is situated in the High-Arctic between the latitudes of 76^{o} and 81^{o} north. On western Spitsbergen, the main island of the Svalbard archipelago, it has been inferred that glaciers generally reached their LIA maximum around 1900 A.D. (Hagen and Liestøl, 1990; Lefauconnier and Hagen, 1990) to 1936 (Mangerud and Landvik, 2007), significantly later than regions at a lower latitude. It is a widespread belief that the LIA represents the most extensive period of Holocene glacial advance on Svalbard, as there are few Holocene ice marginal features that exist beyond LIA moraine sequences (Kristiansen and Sollid, 1987; Mangerud *et al.*, 1992; Werner, 1993; Svendsen and Mangerud, 1997; Snyder *et al.*, 2000).

Fleming *et al.* (1997) remark that whereas the potential importance of glaciers to greenhouse-induced warming has been discussed by several authors (Meier, 1984; Meier, 1990; Oerlemans and Fortuin, 1992), the reconstruction of High-Arctic glaciers has seldom been performed, particularly on Svalbard (Fleming *et al.*, 1997). This study will therefore attempt to provide reconstructions of the size of LIA glaciers by establishing the palaeo ELA of eight cirque glaciers in and around Linnédalen, western Spitsbergen.

A glacier can be divided up into two areas, an accumulation area, where there is a net increase in snow, and an ablation area, where there is a net decrease in snow. The two zones are separated by the ELA (Hambrey and Alean, 2004). The ELA provides a climatically sensitive measure to palaeo-glacier extent (Polissar *et al.*, 2006). When a low ELA is observed in relation to the present ELA, a glacier will have had a greater amount of accumulation than ablation *id est* have a positive mass balance and be growing (Humlum, 2002). Conversely, when a higher ELA is observed compared to present day conditions, a glacier will have experienced a greater amount of ablation compared to accumulation *id est* have a negative mass balance and be shrinking (see figure 1.1) (Hambrey, 1994). The location of the ELA is further complicated by local and regional climate, as well as topography (Benn and Evans, 1998). Such factors can induce anomalous snow accumulation patterns, which can potentially allow glaciers to exist below the regional ELA (*ibid.*). Dolgushin (1961) demonstrates this in cirque glaciers that have formed from wind-blown snow accumulation in the sheltered leeward slopes of the Urals, Russia (Dolgushin, 1961)

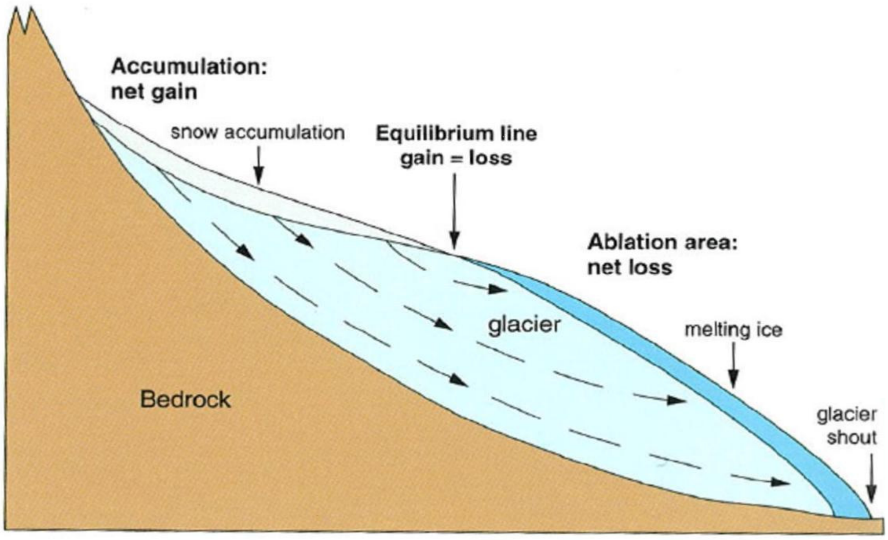


Figure 1.1 A typical cirque glacier has an accumulation area where snow builds up, and an ablation area where snow melts away. The two zones are separated by the ELA where snow loss is equal to snow gain (Hambrey and Alean, 2004)

1.2 Study Area

Linnédalen is located close to the North Atlantic Ocean on the western side of Spitsbergen. The present day regional ELA for glaciers along this coast is in excess of 400 m a.s.l. (Hagen *et al.*, 2003a; Hagen *et al.*, 2003b). The western coast is influenced by the warm Norwegian Current and prevailing winds trend from the south-west. At the northern end of the study area lies Isfjord Radio where the mean annual temperature

(1961-1990) is -5.1^{o}C (Førland *et al*., 1997). The average temperatures in the coldest and warmest months of the year are -12.4^{o}C and +4.8^{o}C respectively (Mangerud and Landvik, 2007). Figure 1.2 illustrates the location of Linnédalen in the context of Svalbard and further depicts the cirques that will make up the study sites of this paper. These sites were largely chosen for their accessibility and from the presence of moraine sequences illustrated on topographical maps.

a)

b)

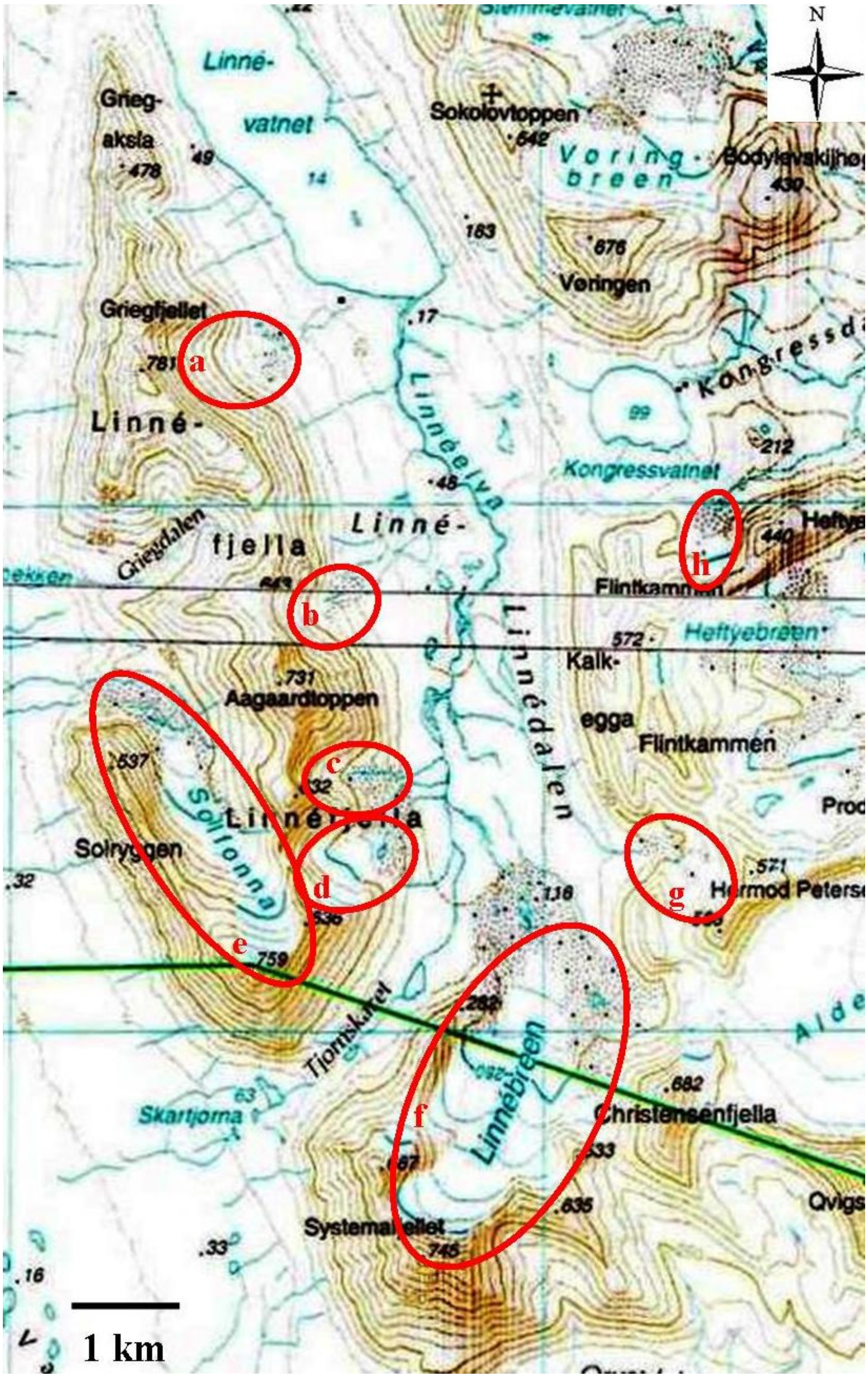


Figure 1.2 a) Map depicting the location of Linnédalen on the West coast of Spitsbergen, Svalbard (modified from Norsk Polarinstitutt, 2000). **b)** Topographical map of Linnédalen depicting the eight areas studied, labelled a-h: a) Grieg Cirque; b) Aagaard Cirque; c) Solryggen North Cirque; d) Solryggen South Cirque; e) Solfonna Cirque; f) Linnébreen; g) Hermod Petersen Cirque; h) Kongress Cirque (modified from Norsk Polarinstiutt, 2008a; Norsk Polarinstiutt, 2008b)

2. METHODOLOGY

2.1 ELA Reconstruction Using Geomorphological and Map Based Techniques

Several different methods have commonly been employed to determine estimated palaeo-ELAs. The methods vary in their approach and all have some limitation or potential for error (Porter, 2001). Nevertheless, the techniques are still utilised as they can provide a very good proxy for past glacier size. Four different ELA reconstruction methods will be used in this investigation.

2.2 Maximum Elevation of Lateral Moraines (MELM)

The MELM technique works on the premise that glacier flow results in a net transport of debris from a glacier's accumulation area to its ablation area (Benn and Evans, 1998). In the ablation zone this debris is deposited as moraine sequences. As lateral moraines are only deposited below the ELA, the method works on the idea that the uppermost altitude of an abandoned lateral moraine marks the palaeo-ELA (Andrews, 1975; Nesje and Dahl, 2000).

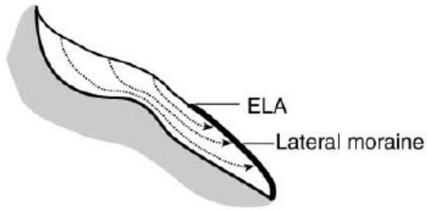


Figure 2.1 The MELM ELA reconstruction technique works on the principle that the palaeo-ELA can be estimated by measuring the altitude of the highest part of a glacier's lateral moraine, as lateral moraines are only deposited below the ELA (Porter, 2001)

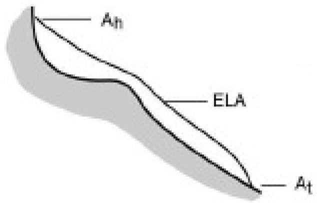
There are some shortcomings with the MELM method however. The assumption has to be made that deposition started at exactly the ELA but this may not always be the case, which would lead to a lower observed ELA than was the case (Nesje and Dahl, 2000). In addition, on steep slopes lateral moraines are often removed via mass movement and erosional processes after ice retreat (Meierding, 1982). In such a situation the MELM approach is likely to underestimate the ELA (Refsnider *et al.*, 2007). What is more, ice cored lateral moraines will likely experience a down-wasting effect after glacier retreat, whilst lateral moraines in general will degrade post glaciation (Benn and Evans, 1998). Such an occurrence would cause a speciously low ELA estimation. Conversely, if glacier retreat is slow, then continued deposition from the glacier will result in a higher ELA measurement (*ibid.*). Furthermore, continued deposition may occur on top of the lateral moraines from steep valley sides, again leading to an overestimation in the height of the ELA.

In this investigation lateral moraine height will be measured using an altimeter to the nearest 0.5 m on both sides of the cirque. The highest lateral moraine will then be taken as the ELA. The altimeter will be set to a fixed point at the start of each measurement sequence and a final reading will be taken at the end of a day's recordings from the same fixed point. Linnévatnet will provide the fixed point for measurements on Grieg cirque, Aagaard cirque, Solryggen North cirque, Solryggen South cirque, Linnébreen and Hermod Petersen cirque. Isfjorden will provide the fixed altitude for measurements taken on Solfonna, whilst Kongressvatnet will provide the fixed altitude for measurements on Kongress cirque. Wherever an altimeter reading is taken, the time and the temperature will be recorded. After data collection, corrections will be made for temperature and pressure throughout the sequence of readings. Pressure data for these corrections will be taken from an automatic weather station deployed in the centre of Linnédalen, approximately 750 m south of Linnévatnet.

2.3 Toe-to-Headwall Altitude Ratio (THAR)

The THAR works by setting the ELA at a fixed ratio between the toe of the former glacier, construed from end moraine sequences, and the top of the valley headwall (Leonard and Fountain, 2003). Figure 2.2 depicts the ELA on an exemplar cirque glacier and demonstrates the equation used to calculate the ELA. Cirque and valley glaciers often have a THAR of 0.35 to 0.40 and accordingly this investigation will calculate THAR palaeo-ELAs using ratios of 0.35 and 0.4 (Meierding, 1982; Murray and Locke, 1989).

a)



b)

$$ELA = A_t + THAR\ (A_h - A_t)$$

Figure 2.2 a) Diagram of the THAR ELA reconstruction method where A_h represents the headwall altitude and A_t represents the glacier-toe altitude (Porter, 2001). **b)** Equation used to calculate the palaeo-ELA

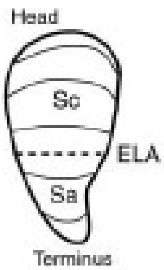
A major problem exists in where to define the headwall limit of a former glacier and this is a very subjective part of the assessment (Nesje and Dahl, 2000; Porter, 2001). Porter (2001) comments how a high, steep headwall can provide a range of ELA estimates that differ by 10s metres (m) to 100s m (Porter, 2001). The THAR method is widely regarded as the crudest of the four methods that will be employed in this survey, as it takes no account of glacier hypsometry or climatic considerations (Benn and Evans, 1998). Nevertheless, it provides a simple and relatively rapid means of past ELA assessment.

In this study, glacier toe heights will be measured in the field using the same altimetry methods outlined in the MELM section above. Again these altimetry values will be corrected for temperature and pressure. Headwall values will be taken from Norsk Polarinstitutt (2008a; 2008b) 1:100,000 topographical maps (Norsk Polarinstiutt, 2008a; Norsk Polarinstiutt, 2008b). Ideal topographic maps would provide contours at 30 m or less (Porter, 2001). The maps available for Svalbard provide contours only at 50 m intervals, and as such, a certain amount of interpolation will be required.

2.4 Accumulation Area Ratio (AAR)

The AAR method is based on the assumption that the accumulation area of a glacier occupies a fixed proportion of the total glacier area (Benn and Gemmell, 1997). Empirical studies of modern glaciers have shown that under steady-state conditions, an AAR of 0.6 can be assumed to characterise cirque glaciers (Meier and Post, 1962; Porter, 1975; Porter, 1977; Kuhn, 1989; Benn and Evans, 1998; Benn and Lehmkuhl, 2000; Nesje and Dahl, 2000; Porter, 2001; Rea and Evans, 2007). The methodology starts with the mapping of a glacier's extent on a topographical map using glacial and geomorphological observations, for instance lateral and end moraines, erratics and trimlines (Porter, 1981). An estimated initial ELA is applied to this palaeo-glacier outline from which contours of the glacier surface are applied in accordance with the topographical map. Below the estimated ELA, glacier contours are convex and above the ELA the contours are concave consistent with glacier flow patterns. The degree of concavity and convexity should increase with distance from the ELA (figure 2.3) (Porter, 2001). The area between each contour can then be used to produce a graphical representation of the glacier's area/altitude distribution, which can then be used to satisfy an AAR of 0.6 (*ibid.*).

a)



b)

$$AAR = \frac{Sc}{Sc + Sa} = 0.6$$

Figure 2.3 a) Method of reconstructing an ELA using the AAR approach, where Sc represents the accumulation area and Sa represents the ablation area (Porter, 2001). **b)** Equation that has to be satisfied for a cirque glacier with an assumed AAR of 0.6

The largest source of error associated with this method is the reconstruction of glacier surface contours. Nevertheless, this source of inaccuracy is considered to be randomly distributed and is not considered to introduce major deviations (Nesje and Dahl, 2000). Additionally, the palaeo-glacier extent is a somewhat subjective operation. Another shortcoming of the AAR reconstruction technique is that little account of glacier area over its altitudinal range is considered (Furbish and Andrews, 1984). Further, Benn and Evans (1998) comment how former glacier ELAs based on a uniformly assumed AAR value may be subject to significant errors if there is a wide range of glacier shapes in the study area (Benn and Evans, 1998).

In this study the ELA estimation will come from map based calculations with palaeo-glacier extent configured from field observations, aerial photography and topographic maps of Linnédalen. Norsk Polarinstitutt (2008a; 2008b) 1:100,000 topographical maps will be computer enhanced to a larger scale and then printed onto 2 millimetre (mm) square paper (Norsk Polarinstiutt, 2008a; Norsk Polarinstiutt, 2008b). From this, the procedure outlined above will then be carried out until an ELA estimation is calculated. Surface debris in the ablation zone can modify the AAR, however field observations and oblique aerial photographs from 1936 would suggest that this was not the case (Mackintosh *et al.*, 2006).

2.5 Balance Ratio (BR)

The BR method takes account of the deficiencies of the AAR approach in that it considers glacier hypsometry. It works on the principle that, for a glacier in state of equilibrium, the total annual accumulation above the ELA must balance that of the total ablation below the ELA (Furbish and Andrews, 1984; Benn and Evans, 1998; Nesje and Dahl, 2000; Rea and Evans, 2007). It further differs from the AAR approach in that it considers glacial area within each altitudinal contour band (Mark and Helmens, 2005).

For this particular investigation, a BR computerised spreadsheet will be used to reconstruct the palaeo-ELAs for Linnédalen. The spreadsheet is a modified version of that produced by Benn and Gemmell (1997). Contour intervals will be set at 50 m and, for ease and consistency, the same palaeo-glacier reconstructions used in the AAR assessment will be used and thus the same areas calculated using the technique described in section 2.4 will be applied.

2.6 Aerial Photography

Aerial photographs exist of Linnédalen from 1936, 1961, 1969, 1990 and 1995. The plan view photographs from 1961, 1969, 1990 and 1995 were taken in mid-August of their respective year, which can be assumed to be at or very close to the end of the ablation season for Svalbard. The pictorial representation of Linnédalen from these four years will provide additional help in the establishment of the location of the MELM before field observations take place. Moreover, they will provide guidance for the AAR and BR palaeo-ELA reconstruction approaches. The 1936 photographs are oblique and are of less use than the plan view photographs.

2.7 Chronology

Evidence for LIA cirque glacier advances in Linnédalen comes largely from unweathered moraines. Due to the nature of the bedrock geology in the valley, other glacial landforms are sparse. The moraines have been correlated to the LIA from the use of aerial photographs from 1936 taken by the Norsk Polarinstitutt.

3. RESULTS

Field altimetry data were collected from the eight study sites. This was then corrected for temperature and pressure, and any repeat measurements were averaged together. The highest MELM for each study site was then compiled together to form the MELM estimated ELA. The map-based reconstructions were further assembled together and a mean result of all five estimations was produced for each site. No weighting was made in favour of any one method. All the results are presented in table 3.1.

	Reconstructed Equilibrium Line Altitude (m a.s.l.)					
Cirque Name	**MELM**	**THAR (0.4)**	**THAR (0.35)**	**AAR (0.6)**	**BR**	**Mean**
Grieg Cirque	121	245	225	195	221	197
Aagaard Cirque	214	200	185	245	248	200
Solryggen North Cirque	262	285	275	280	310	274
Solryggen South Cirque	250	305	290	315	331	282
Solfonna Cirque	214	380	350	285	341	315
Linnébreen	270	285	260	290	305	272
Hermod Petersen Cirque	219	300	285	320	332	268
Kongress Cirque	228	215	210	230	242	218

Table 3.1 The reconstructed ELAs of the eight investigated cirques in the Linnédalen area using the MELM, THAR (0.4), THAR (0.35), AAR (0.6) and BR approaches

Using the data from table 3.1, the author hesitantly suggests a mean LIA ELA between 200 m a.s.l. and 300 m a.s.l. in Linnédalen, with the average mean ELA in the study region equalling 253 m a.s.l.. In addition, there appears to be a lowering of ELAs in the north compared with the south of the region. Data show that the BR method generally produces the highest ELAs. On the whole, the MELM method produces the lowest ELA estimates, closely followed by the THAR (0.35) technique. Places that consistenantly produced low ELAs include Grieg cirque, Aagaard cirque and Kongress cirque. These cirques trend around 50 m lower than the remaining five studied cirques. Furthermore, in looking at the three closest cirques, Solryggen North, Solryggen South and Solfonna, the estimates depict a higher palaeo-ELA on the west of Linnéfjella. Nevertheless in making these comparisons, it may be that one or two exceptionally high reconstructions may be skewing the mean ELA away from that recorded in the field. Indeed, the MELM approach for Solfonna produces a 100 m lower ELA estimation than the mean ELA would suggest and a difference between the highest estimate and lowest estimate of 166 m. In addition, Grieg and Hermod Petersen produce results that have a range of over 100 m. The most comparable data series are found at Kongress (35 m difference in results), Linnébreen (45 m difference in results) and Solryggen North (48 m difference in results).

4. DISCUSSION

4.1 Interpretation of LIA ELAs

The results collected in this investigation indicate a LIA ELA lower than at present, indicating colder conditions and therefore an increase in snow accumulation, from increased precipitation and/or reduced ablation during the LIA. The potential for higher ELAs at Solfonna, Solryggen South and Solryggen North may be the result of the prevailing south-westerly winds that blew through Tjørnskaret. In the field, it was observed to be one of the windiest places in the study area, and the author speculates that the pass may have had a tunnelling effect. This would have exacerbated the effects of snowdrift at these study sites, increasing ablation. Further, it would explain why Linnébreen and Hermod Petersen cirque were impacted less, due to being further away from the Tjørnskaret wind tunnelling effect and from the shelter that they would have received from their own local topographical features. Despite being potentially more exposed to the prevailing wind on the west of Linnéfjella, which might explain the higher ELA here, the author proposes that ice was still able to accumulate in Solfonna due to a north westerly trending valley (figure 4.1).

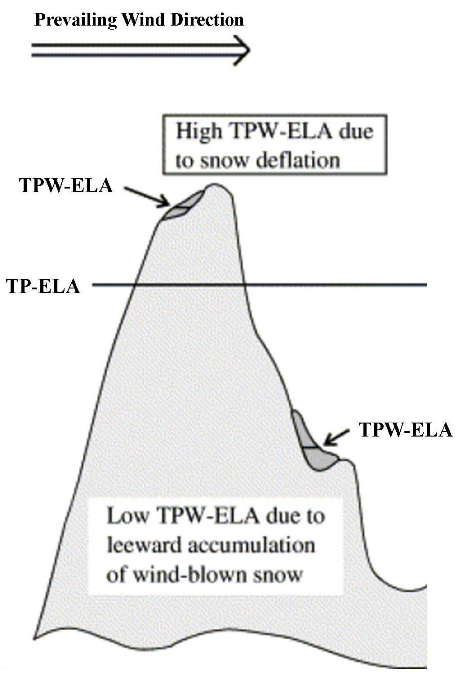


Figure 4.1 The importance of topography for either raising or lowering ELAs is demonstrated here. The abbreviation TPW-ELA stands for temperature, precipitation and wind equilibrium line altitude. The abbreviation TP-ELA stands for temperature and precipitation equilibrium line altitude. Prevailing wind on western Spitsbergen is from the south-west. In the study area it is hypothesised that Tjørnskaret would have acted as a wind tunnel that would have effectively raised ELAs of Solfonna cirque, Solryggen South and Solryggen North. Further north in the Grieg cirque and Aagaard cirque, it is conjectured that Linnéfjella provided enough shelter to lower ELAs through the positive accumulation of snowdrift (modified from Dahl *et al.*, 2003)

Approximately 1.5 kilometres (km) north of Grieg cirque, another potential LIA cirque was identified and investigated with the idea of establishing a LIA ELA. It was decided that the investigated hollow was not a cirque glacier however, and was more likely a glacieret, a thin ice patch where accumulation may not have quite reached high enough levels to flow out of the cirque. It is possible that glacier motion may have once been initiated as the snow patch extended over 30 m from the base of its back wall. At such a distance forces imposed by weight and surface gradient overcome internal resistance and the ice can move (Ballantyne and Benn, 1994). Nevertheless, no discernable moraine features were found and the glacieret was likely formed by snow drift and avalanches, assisted by topographic shelter from Linnéfjella.

The LIA ELA of the Grieg cirque can be compared to that of Snyder *et al.* (2000) whom used the AAR methodology. Using a value of 0.6 they produced an ELA of between 230 and 280 m a.s.l. (Snyder *et al.*, 2000). This value provides a higher LIA ELA than the same AAR reconstruction in this paper, and further a higher LIA ELA than the mean altitude. The author attributes this difference to the subjective nature in the AAR technique, something which is not assisted by the small scale topographic maps available for reconstruction exercises on Svalbard. Mangerud and Svendsen (1990) produced an ELA estimate of between 250 m and 300 m for Linnébreen (Mangerud and Svendsen, 1990). From the assumption that their established heights, as well as the palaeo-ELAs presented in this study, are accurate, it would suggest a rise of some 10s m has occurred in the ELA during the past eighty years. This statement is supported by Snyder *et al.* (2000). In contrast, in north-west Spitsbergen around Kongsfjorden, a 100 m lowering of ELAs during the LIA has been reported compared to today (Liestøl, 1988). This would indicate that greater warming and/or a decrease in the accumulation of snowfall has been experienced since the end of the LIA in Kongsfjorden.

4.2. Methodology Review

As was suggested in the methodology there are inherent problems with all of the ELA reconstruction techniques. Firstly, map based reconstruction techniques, namely THAR, AAR and BR are a subjective assessment. For the THAR method, both the headwall and toe altitudes have to be estimated, whilst with the AAR and BR reconstructions the entire area of the palaeo-glacier has to be predicted. This is further complicated by the small scale maps available for Svalbard where contours are set at 50 m. This requires a certain level of interpolation and as such values will vary for each individual's reconstruction depending on their own interpretation of the topographic maps. The small scale maps will thus generate greater variation in ELA estimates for small differences in either chosen toe and headwall values or in palaeo-glacier area. The author proposes these factors in the difference between the results presented for Grieg cirque in this paper and in Snyder *et al.* (2000).

The MELM approach is also potentially flawed. Problems were experienced in the field in the determination of the exact upper limit of the lateral moraine. Aerial photography assisted greatly with this problem, nevertheless, it is high plausible that someone repeating this study may produce ELA estimates 10s m different to results printed here. Furthermore, the predominant underlying geology of Linnéfjella is highly erodible phyllite, and being so highly erodible, it was often difficult to distinguish between the upper limit of a lateral moraine and skree or weathered bedrock (Snyder *et al.*, 2000). Lateral moraines had also to contend with steep valley sides in several of the cirques, which may have led to an underestimation in the ELA. Additionally, some of the lateral moraines had been eroded and it is almost certain that all of the lateral moraines will have experienced some amount of downwasting since the end of the LIA. This in part would help to explain the much lower ELA values produced using this method. If MELM ELA figures were used on their own, it would suggest that the LIA ELAs in the investigated area were between 30 m and 80 m lower than late 20th Century ELAs in the region.

It should be noted that altimetry values were produced by the use of a handheld altimeter. This was because a Global Positioning System (GPS) could not pick up enough satellites at such a high latitude in order to provide accurate altitude readings. The human error in the use of a handheld altimeter is considered to have only a negligible impact upon results. It is for this reason, combined with the small scale maps available for the Linnédalen region, that toe readings were taken using the altimeter. By combining map and field data there is a greater potential for error, yet end moraine sequences tend to be deposited on relatively flat topography, reducing the significance somewhat. Indeed, altimeter heights were chosen for use because they could potentially provide a more detailed ELA reconstruction than map based reconstruction alone. Further, it was considered much easier to establish where the glacier toe was in the field than on a map.

Despite the flaws in all of the ELA reconstruction approaches, the author largely considers the MELM procedure to be the most effective for use on Svalbard because of the small scale of topographic maps available. Additionally, despite producing lower ELA estimates from the down wasting of ice cored moraines, the MELM approach provides the most precise palaeo-ELA estimate compared with the THAR, AAR and BR techniques for Linnédalen. So long as one of the two lateral moraines can be found for assessment that has not been: deposited on a steep slope; has had material added to it by debris after deposition; had a palaeo-glacier that experienced periods of re-advance in a time of generalised retreat; or been extensively eroded, then a slightly lowered, but nonetheless reliable, past ELA can be established.

4.3 The Value of Field and Aerial Photography in the MELM Approach

MELM ELA estimates were considerably assisted by field photography and aerial photography. Having a plan view of a study area provided by aerial photography was a real help in this investigation. Seeing things on the ground when a scientist is right in the middle of what they are looking at is often very difficult, so having an initial idea of conditions in a cirque considerably abetted this investigation. In addition, when in the field, there were occasions whereby taking a photograph of a cirque and using the zoom function, features, for instance the continuation of a lateral moraine over 100s m, became more prominent and easier to interpret. An example of this is shown in figure 4.2.

Figure 4.2 Photography can greatly assist in field observations. Here, what is interpreted as a LIA lateral moraine in the Solfonna cirque is highlighted, something that was not discernable from initial field observations.

4.4. Norsk Polarinstitutt 1:100,000 Topographic Maps – A Comment

During the reproduction of LIA ELAs from the use of map based techniques, a marked difference between certain field observations and the Norsk Polarinstitutt 1:100,000 topographic maps were noted. Several altimetry readings for toe and lateral moraines were recorded at a sufficiently lower elevation than they appear on the maps. Examples of this can be found at Kongress cirque where from the topographic maps, a toe estimate would be approximately 25 m to 50 m higher than what was recorded in the field. In addition, in Hermod Petersen cirque, moraine sequences stretch from below 200 m to above 300 m, whereas from field altimetry the toe was recorded at 185m with the highest discernable LIA moraine being located at 219m. This illustrates another problem when using small scale topographic maps to reproduce LIA ELAs. It may be possible that what has been inferred as moraine is in fact the product of mass movement processes. Further, the Norsk Polarinstitutt provide no age constraint to any moraine formations, and so scientists who wish to produce LIA ELA estimates have to assume that all moraine from previous glacial advances has been overridden by LIA glaciers. Nevertheless, there is the possibility that, due to Svalbard's inaccessible nature, mapping errors have occurred. This is a serious consideration, in that the Norsk Polarinstitutt (2008) maps have been produced predominantly using aerial photographs from 1990 and 1995, as well as glacier fronts at sea level being produced by Landsat images from 1998. The issue of glacier retreat was recorded in the field at Solfonna cirque, for example, where an anticipated 2.5 km glacier had retreated beyond recognition from the map (figure 4.3). The fact that many of these cirques are now, or are virtually, ice free, supports Snyder *et al.* (2000) statement that there exists a sensitive threshold on ice accumulation in the cirques of

Linnédalen. What impact such climatic sensitivity may have on the larger glaciers of western Spitsbergen is not the premise of this paper, however.

Figure 4.3 A photograph of Solfonna cirque trending up cirque (south-east). A rapid decline in the glacier can be seen compared to the level of ice expected from the Norsk Polarinstitutt (2008b) 1:100,000 topographic map (for an indication of expected ice see figure 1.2 b).

4.5 Future Work

This project lends itself to several potential avenues of future work. In terms of field observations and the MELM technique, it would be of interest to compare to the cirques of Linnédalen with other cirques along the west coast, form both lower and higher latitudes. Present day western coast ELAs differ quite considerably, being higher in north-west coastal localities than in south-west coastal regions (Hagen *et al.*, 2003a; Hagen *et al.*, 2003b). Moreover, within the vicinity of Linnédalen, the west Grønfjorden region appears to hold several cirque glaciers that would seem to have LIA moraine sequences. What is more, it would be interesting to model the LIA ELAs from west Spitsbergen to east Spitsbergen to measure any potential rise in localised ELA. This rise would be anticipated due to a decrease in distance from the main direct precipitation source (the North Atlantic) and hence the author would anticipate a fall in precipitation, parallel with that experienced on Svalbard today (Humlum, 2002).

In terms of future work on topographic map based LIA ELA reconstructions, a refinement of previous glacier extent in Linnédalen region could be readily achieved. Furthermore, constraints on the Benn and Gemmell (1997) spreadsheet used to calculate the BR ELA estimate would potentially combat ELA overestimation for the western Svalbard region.

5. CONCLUSSION

- Averaged reconstructions in Linnédalen region suggest a LIA ELA of between 200 m a.s.l. and 300 m a.s.l.. This is approximately 100 m to 200 m or more lower than the western coast of Spitsbergen at present (Hagen *et al.*, 2003a; Hagen *et al.*, 2003b). There appears to be a lowering in the ELA in the north of the valley compared to the south, which may be the result of Tjørnskaret acting as a wind tunnel and exacerbating the impact of snowdrift ablation around Solfonna, Solryggen North and Solryggen South. Glaciers further north would receive greater protection from Linnéfjella against snowdrift ablation and may in fact benefit from the positive accumulation of snowdrift.
- Care has to be taken in using reconstruction techniques that rely on topographic maps in places, such as Svalbard, where only small scale maps are available. Potential problems can also arise from using the MELM technique because of down-wasting of ice cored moraines and from the difficulty in discerning where ELAs reach their maximum, either from slow glacier retreat or from the product of erosional and mass movement activity in steep sided cirques.
- Despite producing a lower ELA estimate for LIA glaciers, it is the opinion of the author that the MELM approach to ELA reconstruction engenders the most accurate estimations in Svalbard. This is due to the small scale, as well as possible inaccuracies contained within, the Norsk Polarinstitutt (2008) maps that have largely been produced on the basis of aerial photographs from 1990 and 1995, with glacier fronts mapped using Landsat images from 1998.

ACKNOWLEDGEMENTS

The original field data presented in this written work was collected between 22nd July 2008 and 10th August 2008 as part of an International Polar Year (IPY) joint collaboration between the United States National Science Foundation (US NSF) Research Experience for Undergraduates (REU) programme and the University Centre in Svalbard (UNIS) Arctic Geology 212 course, 'Holocene and Modern Climate Change in the High Arctic, Svalbard'.

The author of this paper wishes to foremost thank Mike Retelle for the inspiration to undertake this project and for the invaluable advice he bestowed both in and out of the field. Further, to all the REU/UNIS students and associates, in particular Maya Wei-Haas, Leo Sold and Anthony Novak, for their helpful work, advice and companionship in the field. Logistical support was provided by UNIS, US NSF REU programme and Isfjord Radio. A final thanks should go to everyone at Isfjord Radio, who were so understanding to our needs and made this field season so much more pleasant.

REFERENCES

Andrews, J.T. (1975) *Glacial Systems: An Approach to Glaciers and their Environments*. North Scituate, Massachusetts: Duxbury Press

Ballantyne, C.K., Benn, D.I. (1994) 'Glaciological Constraints on Protalus Rampart Development'. *Permafrost and Periglacial Processes* 5, 145-153
Benn, D.I., Gemmell, A.M.D. (1997) 'Calculating Equilibrium Line Altitudes of Former Glaciers by the Balance Ratio Method: A New Computer Spreadsheet'. *Glacial Geology and Geomorphology* (http://ggg.qub.ac.uk/papers/full/1997/tn011997/tn01.html)
Benn, D.I., Evans D.J.A. (1998) *Glaciers and Glaciations*. London: Arnold
Benn, D.I., Lehmkuhl, F. (2000) 'Mass Balance and Equilibrium-Line Altitudes of Glaciers in High-Mountain Environments'. *Quaternary International* 65/66, 15–29
Dahl S.O., Bakke J., Lie O., Nesje A. (2003) 'Reconstruction of Former Glacier Equilibrium-Line Altitudes Based on Proglacial Sites: An Evaluation of Approaches and Selection of Sites'. *Quaternary Science Reviews* 22(2), 275-287
Dolgushin, L.D. (1961) 'Main Features of the Modern Glaciation of the Urals'. *IASH* 54, 335-347
Fleming, K.M., Dowdeswell, J.A., Oerlemans, J. (1997) 'Modelling the Mass Balance of Northwest Spitsbergen Glaciers and Responses to Climate Change'. *Annals of Glaciology* 24, 203-210
Førland, E., Hanssen-Bauer, I., Nordli, P. (1997) 'Climate Statistics and Longterm Series of Temperatures and Precipitation at Svalbard and Jan Mayen'. *Norwegian Meteorological Institute, Report 21/97*, 1-72
Furbish, D.J., Andrews, J.T. (1984) 'The Use of Hypsometry to Indicate Long-term Stability and Response of Valley Glaciers to Changes in Mass Transfer'. *Journal of Glaciology* 30, 199–211
Grove, J.M. (1988) *The Little Ice Age*. London: Methuen
Grove, J.M. (2004) *Little Ice Ages: Ancient and Modern*. London: Routledge
Hagen, J., Liestøl, O. (1990) 'Long-Term Glacier Mass-Balance Investigations in Svalbard'. *Annals of Glaciology* 14, 102-106
Hagen, J.O., Kohler, J., Melvold, K., Winther, J.G. (2003a) 'Glaciers in Svalbard: Mass Balance, Runoff and Freshwater Flux'. *Polar Research* 22, 145-159
Hagen, J., Melvold, K., Pinglot, F., Dowdeswell, J. (2003b) 'On the Net Mass Balance of the Glaciers and Ice Caps in Svalbard, Norwegian Arctic'. *Arctic Antarctic and Alpine Research* 35, 264-270
Hambrey, M. (1994) *Glacial Environments*. London: CRC Press
Hambrey, M., Alean, J. (2004) *Glaciers*. Cambridge: Cambridge University Press
Kristiansen, K.J., Sollid, J.L. (1987) 'Svalbard, Jordartskart 1:1,000,000. Nasjonalatlas for Norge'. *Geografisk Institutt, Univeritet i Oslo*
Humlum, O. (2002) 'Modelling Late 20th-Century Precipitation in Nordenskiöld Land, Svalbard, by Geomorphic Means'. *Norsk Geografisk Tidsskrift* 56, 96-103
Kuhn, M. (1989) 'The Response of the Equilibrium Line to Climate Fluctuations: Theory and Observations'. In *Glacier Fluctuations and Climate Change* Oerlemans, J. (ed.), 407–417. Dordrecht: Kluwer
Lefauconnier, B., Hagen, J. (1990) 'Glaciers and Climate in Svalbard: Statistical Analysis and Reconstruction of the Brøggerbreen Mass Balance for the Last 77 Years'. *Annals of Glaciology* 14, 148-152
Leonard, K.C., Fountain, A.G. (2003) 'Map-Based Methods for Estimating Glacier Equilibrium-Line Altitudes'. *Journal of Glaciology* 49(166), 329-336

Liestøl, O. (1988) 'The Glaciers of the Kongsfjorden Area, Spitsbergen'. *Norsk Geografisk Tidsskrift* 42, 231–38
Mackintosh, A.N., Barrows, T.T., Colhoun, E.A., Fifield, L.K. (2006) 'Exposure Dating and Glacial Reconstruction at Mt. Field, Tasmania, Australia, Identifies MIS 3 and MIS 2 Glacial Advances and Climatic Variability'. *Journal of Quaternary Science* 21(4), 363–376
Mangerud, J., Svendsen, J.I. (1990) 'Deglaciation Chronology Inferred from Marine Sediments in a Proglacial Lake Basin, Western Spitsbergen, Svalbard'. *Boreas* 19, 249–72
Mangerud, J., Bolstad, M., Elgersma, A., Helliksen, D., Landvik, J.Y., Lønne, I., Lycke, A.K., Salvigsen, O., Sandahl, T., Svendsen, J.I. (1992) 'The Last Glacial Maximum on Western Svalbard'. *Quaternary Research* 38, 1-31
Mangerud, J., Landvik, J.Y. (2007) 'Younger Dryas Cirque Glaciers in Western Spitsbergen: Smaller than During the Little Ice Age'. *Boreas* 36, 278-285
Mann, M. E., Bradley, R. S., Hughes, M. K. (1999) 'Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations'. *Geophysical Research Letters* 26, 759–762
Mark, B.G., Helmens, K.F. (2005) 'Reconstruction of Glacier Equilibrium-Line Altitudes for the Last Glacial Maximum on the High Plain of Bogotá, Eastern Cordillera, Colombia: Climatic and Topographic Implications'. *Journal of Quaternary Science* 20(7–8), 789–800
Meier, M.F., Post, A.S. (1962) Recent Variations in Mass Net Budgets of Glaciers in Western North America. International Association of Scientific Hydrology 58, 63-77
Meier, M.F. (1984) 'Contribution of Small Glaciers to Global Sea Level'. *Science* 226(4681), 1418-1421
Meier, M.F. (1990) 'Reduced Rise in Sea Level'. *Nature* 343(6254), 115-116
Meierding, T. C. (1982) 'Late Pleistocene Glacial Equilibrium-Line Altitudes in the Colorado Front Range: A Comparison of Methods'. *Quaternary Research* 18, 289–310
Murray, D.R., Locke, W.W.III (1989) 'Dynamics of the Late Pleistocene Big Timber Glacier, Crazy Mountains, Montana, U.S.A.'. *Journal of Glaciology* 35, 183–190
Nesje, A., Dahl, S.O. (2000) *Glaciers and Environmental Change*. New York: Oxford University Press
Norsk Polarinstitutt (2000) Norsk Polarinstitutt website. Available at: http://miljo.npolar.no/temakart/images/maps/GeneralMapOfSvalbardAndKeymap.gif [Access date: 01 August 2008]
Norsk Polarinstitutt (2008a) *Svalbard 1:100,000 series: B9 – Isfjorden*. Tromsø: Norsk Polarinstitutt
Norsk Polarinstitutt (2008a) *Svalbard 1:100,000 series: B10 – Van Mijenfjorden*. Tromsø: Norsk Polarinstitutt
Oerlemans, J., Fortuin, J.P.F. (1992) 'Sensitivity of Glaciers and Small Ice Caps to Greenhouse Warming'. *Science* 258(5079), 115-117
Ogilvie, A.E.J., Jónsson, T. (2001) '"Little Ice Age" Research: A Perspective from Iceland'. *Climatic Change* 48, 9-52
Polissar, P.J., Abbott, M.B., Wolfe, A.P., Bezada, M., Rull, V., Bradley, R.S (2006) 'Solar Modulation of Little Ice Age Climate in the Tropical Andes'. *Proceedings of the National Academy of Sciences* 103(24), 8937-8942

Porter, S.C. (1975) ‘Equilibrium Line Altitudes of Quaternary Glaciers in the Southern Alps, New Zealand’. *Quaternary Research* 5, 27–47
Porter, S.C. (1977) ‘Present and Past Glaciation Threshold in the Cascade Range, Washington State, USE: Constraints Provided by Palaeoenvironmental Reconstructions’. *The Holocene* 11, 607–611
Porter, S.C. (1981) ‘Glaciological Evidence of Holocene Climatic Change’. In *Climate and History* Wigley, T.M.L., Ingram, M.J., Farmer, G. (eds.), 82-110. Cambridge: Cambridge University Press
Porter, S.C. (2001) ‘Snowline Depression in the Tropics During the Last Glaciation’. *Quaternary Science Reviews* 20, 1067-1091
Rea, B.R., Evans D.J.A. (2007) ‘Quantifying Climate and Glacier Mass Balance in North Norway During the Younger Dryas’. *Palaeogeography, Palaeoclimatology, Palaeoecology* 246, 307–330
Refsnider, K.A., Laabs, B.J.C., Mickelson, D.M. (2007) ‘Glacial Geology and Equilibrium Line Altitude Reconstructions for the Provo River Drainage, Uinta Mountains, Utah, U.S.A.’. *Arctic, Antarctic and Alpine Research* 39(4), 529–536
Snyder, J.A., Werner, A., Miller, G.H. (2000) ‘Holocene Cirque Glacier Activity in Western Spitsbergen, Svalbard: Sediment Records from Proglacial Linnévatnet’. *The Holocene* 10(5), 555-563
Svendsen, J.I., Mangerud, J. (1997) ‘Holocene Glacial and Climatic Variations on Spitsbergen, Svalbard’. *The Holocene* 7(1), 45-57
Werner, A. (1993) Holocene Moraine Chronology, Spitsbergen, Svalbard: Lichenometric Evidence for Multiple Neoglacial Advances in the Arctic. The Holocene 3, 128–37