Reconstruction of former glacier equilibrium-line altitudes based on proglacial sites: an evaluation of approaches and selection of sites

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Abstract

Various approaches are used to record variations in glacier activity and equilibrium-line altitudes (ELAs) based on proglacial sites (lacustrine and terrestrial). These approaches are based on a conceptual model of glacier-meltwater induced sedimentation in which the minerogenic (nonorganic) component of the sediments is related to the occurrence of a glacier in the catchment. The principal coupling to former glacier activity and ELAs is common for these approaches. However, different methods and techniques may complement each other, and both possibilities and limitations are demonstrated. Site selection for reconstructing variations in glacier activity/ELAs is evaluated and critical factors are discussed. Rerouting of glacier meltwater streams across local watersheds in combination with proglacial sites gives a distinct on/off signal for former glacier activity/ELAs. Together with representative lateral moraines of known age, local watersheds are important for calibrating reconstructed glacier activity/ELAs based on a chain of proglacial lakes. Based on the ‘modern analogue principle’, various proxies can record whenever glaciers existed in a catchment. In a chain of proglacial lakes with different sensitivity to record variations in glacier activity/ELAs, these proxies can be calibrated against independent records. For one-site approaches, however, variations in glacier activity/ELAs depend on the interpretation and sensitivity of the proxies used.

1. Introduction

Beyond the time span covered by observed mass-balance measurements and historical records, little was known until recently about continuous variations in equilibrium-line altitudes (ELAs) on Norwegian glaciers. Former ELAs based on the maximum altitude of lateral moraines only reflect shorter periods when the glaciers attained steady state in advanced positions beyond later glacier advances. With the exception of some few glaciers in the continental eastern Jotunheimen (e.g. Matthews and Shakesby, 1984) and at the maritime Folgefonna (Bakke et al., 2000), the marginal moraines formed by glacier advances after the Erdalen Event (Preboreal/Boreal transition; ca 10,000 cal. BP) were erased by the Little Ice Age advance (ca AD 1750) in southern Norway (Matthews, 1991; Dahl and Nesje, 1994). Hence, variations in the ELA based on lateral moraines cannot be used for most of the Holocene in this region.

To avoid this problem, lacustrine and terrestrial deposits in proglacial lakes and bogs beyond the maximum Little Ice Age glacier position have been used to reconstruct periods of former glacier activity within a catchment. Erosion along the glacier sole produces rock floor consisting of clay and silt, and this is transported downstream as suspended material in proglacial meltwater streams (Fig. 1). In contrast to normally transparent nonglacial streams, turbid proglacial meltwater streams typically deposit accumulations of bluish-grey sandy and/ or clayey silt that can be used as a signature for the existence of glaciers within the catchment (e.g. Karlén, 1976). With no glaciers in the catchment, lacustrine sediments with a higher organic content (gyttja) dominate in the proglacial lakes, while peat or gyttja accumulate at the terrestrial sites.

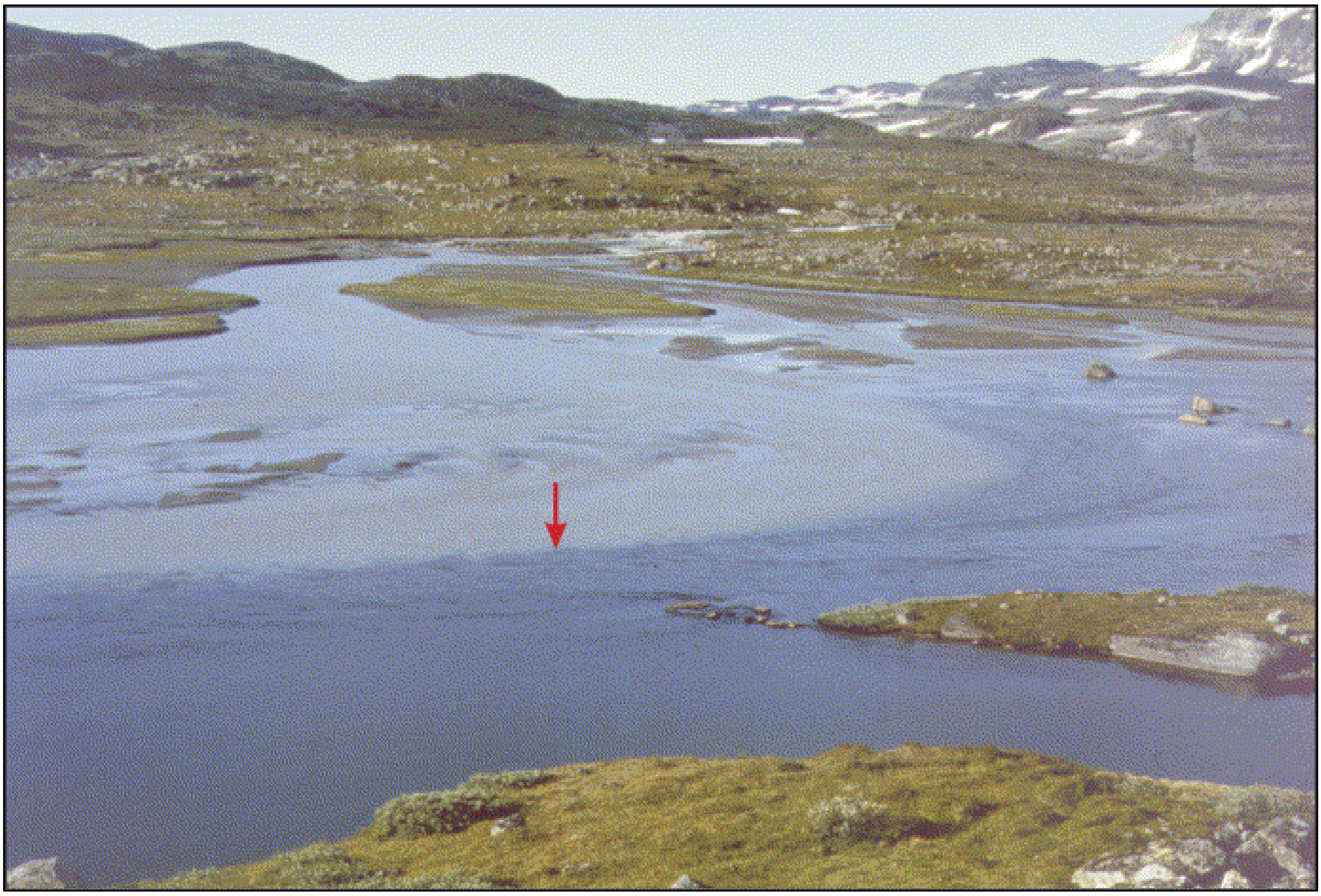

Fig. 1. Photo showing the sharp contrast indicated by red arrow between a turbid glacier meltwater stream from Hardangerjøkulen and a clear nonglacial stream just east of Finse, central southern Norway. The erosion along the glacier sole produces rock flour consisting of clay and silt, and transported downstream as suspended material this gives proglacial meltwater streams their characteristic green-grey colour. Turbid proglacial meltwater streams typically deposit bluish-grey sandy and/or clayey silt that can be used as a signature for whenever upstream glaciers existed. (Photo: S. O. Dahl).

Changes in mean ablation-season temperature (1 May–30 September) and winter precipitation (1 October–30 April) are reflected as variations in the ELA (cf. Andrews, 1975). Based on the mean ablation-season temperature and winter precipitation at the ELA of Norwegian glaciers in different climatic regimes, an exponential relationship has been demonstrated (Dahl et al., 1997, and references therein). This relationship implies that if either the winter precipitation or the ablation-season temperature at the ELA is known, the other factor can be calculated. It also implies that if the former ELA is known, it is possible to calculate how the other parameter has fluctuated (Dahl and Nesje, 1996). Biological proxies (e.g. beetles, chironomids, mites, pine-tree limits, plant-macro fossils, pollen, etc.) from sites not influenced by glacier meltwater or streams from 'permanent' snowfields can be used as independent proxies for summer temperature, while the potential for reconstructing continuous variations in the ELA depends on the number and type of ELA-related proglacial sites at each glacier.

In recent years, a number of curves showing Holocene ELA fluctuations have been published from various regions of southern Norway. Except for the tentative curve of Liestøl (1969), both relative reconstructions (Nesje and Dahl, 1991; Nesje and Kvamme, 1991; Nesje et al., 1991; Matthews and Karlén, 1992) and absolute reconstructions (Dahl and Nesje, 1996; Nesje et al., 2001) have been primarily based on proglacial sites. In the relative reconstructions of Nesje and Kvamme (1991) and Nesje et al. (1991) a combination of proglacial sites and independent palynological data was used, while the ELA curve of Matthews and Karlén (1992) was based on proglacial sites reflecting glaciers at different altitudes. Dahl and Nesje (1996) used four proglacial sites with different sensitivity to variations in glacier size (GS) in the absolute reconstruction of former ELAs at Hardangerjøkulen, while the absolute reconstruction of former ELAs from the Jostedalsbreen region (Nesje et al., 2001) took into account various sediment parameters (weight loss-on-ignition, grain-size analyses, etc.) and sites related to other glaciers in the area to overcome the problem(s) of a one-site approach.

The objective of this paper is to evaluate approaches and site selection when using proglacial sites to reconstruct former glacier activity/ ELAs, and to discuss the general principles behind the calibration and interpretation of these field- and laboratory-based 'empirical' relationships.

2. Methods reflecting glacier activity

The physical processes in glacial sedimentary environments are often complex (e.g. Ashley et al., 1985). However, a number of methods and techniques have been used to record glacier activity based on proglacial lacustrine and terrestrial sites. The methods are based on a conceptual model of glacier-meltwater induced sedimentation in which the minerogenic (nonorganic) component of the sediments is related to the occurrence of a glacier in the catchment (e.g. Karlén, 1981; Leonard, 1985). The organic component depends on many factors, including bedrock lithology and vegetation cover, local climate (temperature, precipitation, wind), size and aspect of the catchment and the lake, water depth and temperature, coverage of superficial sediments in the catchment, colluvial activity related to slope angles around the lake, as well as anthropogenic impact. The minerogenic component in proglacial lakes depends in addition on factors such as transport distance and the number of intervening lakes acting as sediment traps (Smith, 1978). In most lakes the organic component is much smaller than the minerogenic component, but the relative importance of these components is to a large extent site- and/or area dependent. Hence, Matthews and Karlén (1992) argued for the use of representative nonglacial lakes as 'control lakes' in connection with the use of proglacial lakes in the study of glacier fluctuations. The contrast between these two lake types then clarifies the glacial signal.

Due to the large colour variations (light-/bluish grey to dark brown) with and without a glacier in the catchment, visual description of the layers in a core or section using a Munsell colour chart is a useful first approach. This should be supported or supplemented by various field and laboratory methods and techniques:

• Mineral magnetic susceptibility commonly reflects the concentration of magnetic minerals (e.g. Thompson and Oldfield, 1986), and may be used as an indicator of erosion and transport of clastic sediments which can be linked to glacier activity (e.g. Snowball, 1993; Leemann and Niessen, 1994; Snowball and Sandgren, 1996).

• X-ray diffraction analyses with low-density values may indicate high sediment density and hence increasing glacier activity (e.g. Karlén and Matthews, 1992; Matthews and Karlén, 1992; Leemann and Niessen, 1994; Souch, 1994).

• Weight loss-on-ignition (LOI) estimates the organic content of lacustrine sediments (Dean, 1974; see Heiri et al., 2001, for laboratory procedures), and can together with derived parameters (minerogenic material, dry weight, water content, etc.) be linked to glacier variations (e.g. Karlén, 1976; Leonard and Leonard; Nesje; Nesje and Nesje; Souch, 1994; Snowball and Sandgren, 1996; Menounos, 1997; Matthews et al., 2000).

• Grain-size variations of especially clay and silt may be linked to glacier fluctuations (e.g. Leemann and Niessen, 1994; Matthews et al., 2000; Nesje et al., 2001; see Blott and Pye, 2001, for the statistical treatment of grain size distribution).

• Occurrence and thickness of clastic varves reflect variations in glacier activity (e.g. Leemann and Niessen, 1994; Leonard, 1997).

• Bulk density is the ratio of the mass of dry (wet) solids to the bulk volume of the sediment, and may be used to record former glacier variations/ELAs (e.g. Leonard, 1997; Menounos, 1997).

• Lithological changes in the recorded sequence or core may reflect the occurrence of glaciers in the catchment and/or variations in glacier extent (e.g. Svendsen and Mangerud, 1997; Matthews et al., 2000).

The principal coupling to former glacier activity/ELAs is common for all these methods and techniques. In Fig. 2 both possibilities and limitations are illustrated in the schematic coupling between weight LOI and former glacier magnitude/ELA, and the glacier events reflect what is typically recorded in a core from a Norwegian proglacial lake with a temperate glacier in the catchment. The proglacial lake is located so far downstream for the glacier that (visible) turbid meltwater only enters the site during the maximum late spring/early summer flood at present. This can also easily be recorded by the bare eye in the top sediments of the core. In periods when the glacier is much smaller or nearly melted away, no visible turbid glacier meltwater enters the proglacial lake and the relative accumulation of organic sediments in the lake is much higher. The occurrence of an active glacier in the catchment cannot be recorded in the sediments by the bare eye, and only various laboratory techniques can detect an input of glacier-induced sediments to the lake. In periods when the glacier is much bigger than at present (in this example, during the early deglaciation), the influence of glacier-induced sedimentation in the proglacial Lake may be so high that variations in glacier magnitude are difficult to detect or separate out by the available laboratory methods. The main problems concerning the interpretation and calibration of these parameters are thus related to when the glacier was nearly melted away, or when it was so large that the used proxy lacked sensitivity to record variations in GS. However, the various methods may complement each other.

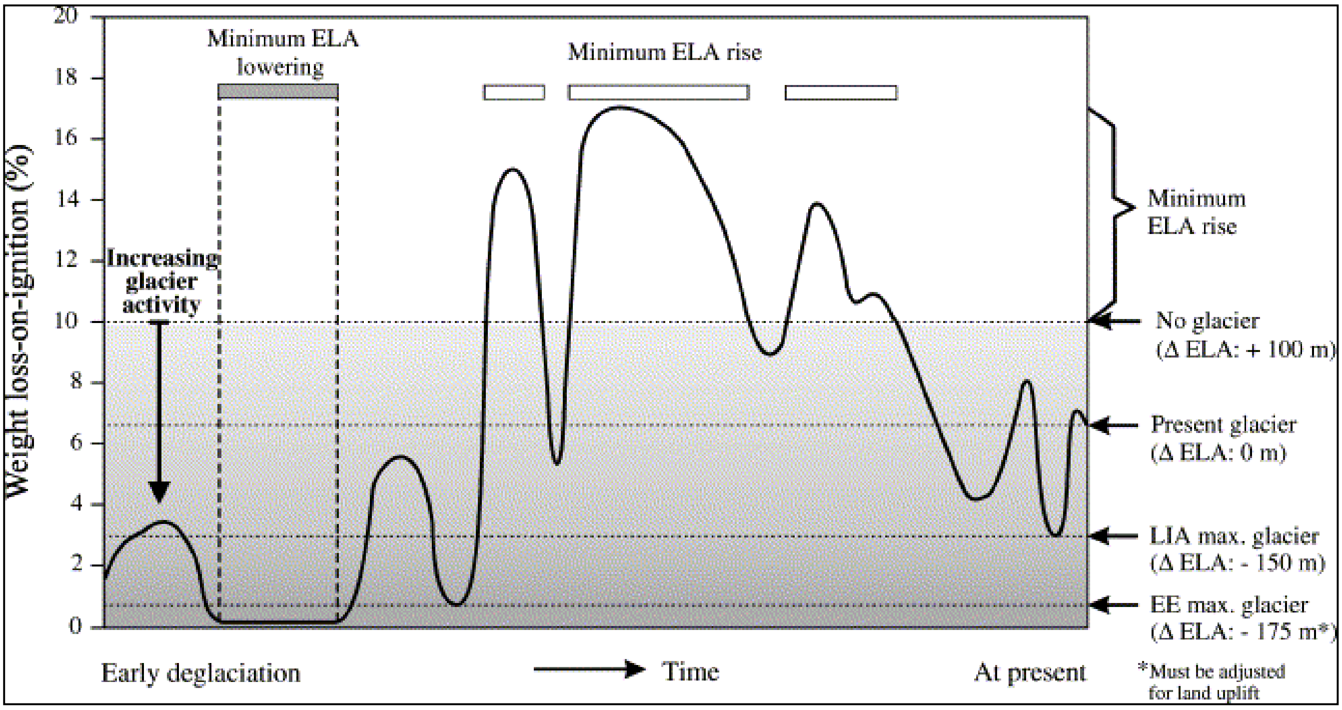

Fig. 2. Schematically illustrated with weight LOI, both possibilities and limitations in the principal coupling between various proxies and variations in glacier activity/ELAs are shown. LIA=Little Ice Age, EE=Erdalen Event. See text for further explanation and discussion.

Both as a link to other palaeoclimatic proxies and as a tool to investigate glacier activity, age control of events are essential. In studies of glacier fluctuations prior to the Little Ice Age maximum several methods have been used to obtain age–depth control:

• By measuring the magnetic declination versus sediment depth, magnetic declination records can be compared with the well-dated master curve of Lake Windermere (Creer and Tucholka, 1983). Assuming synchronous oscillations in the two magnetic declination records this can be used as a dating method (see Snowball, 1993; Leemann and Niessen, 1994, for details).

• The thickness and grain-size distribution in annual clastic glacial varves, if continuous, may represent an annually resolved record of glacier activity. However, the rhythmites in a sequence must be confirmed as real varves in the sense of De Geer (1912) before they can be used for age–depth control (e.g. Leemann and Niessen, 1994; Leonard, 1997).

• Radiocarbon dating tends to be the most important dating method for reconstructing former glacier activity. Recent comparisons between dated bulk sediment and macrofossil samples from various lakes often show marked discrepancies, and radiocarbon chronologies from lake sediments are often based on AMS-radiocarbon dated terrestrial plant macrofossils (e.g. Barnekow et al., 1998). However, on certain sites and under certain conditions, AMS dates on terrestrial plant macrofossils are not superior to bulk sediment samples (e.g. Gulliksen et al., 1998), and the most reliable chronologies may be obtained not from terrestrial plant macrofossils, but from that part of the sediment fraction (the 'humic' NaOH-soluble component), where there is no contamination by older carbon residues (Lowe and Walker, 2000).

Age estimates should be given as calibrated years before present (BP) in accordance with INTCAL98 for radiocarbon dates (Stuiver et al., 1998). As sedimentation rates vary with and without a glacier in the catchment of proglacial lakes, both the initiation and the termination of glacier episodes should be dated. Hence, age–depth control in proglacial lakes relies on linear interpolation within periods with and without a glacier in the catchment.

3. Site selection

To find an area with proglacial sites suitable for reconstructing variations in former GS/ELAs, several factors must be evaluated:

• The current glaciated area in the catchment must be ‘appropriate’ for recording the amplitude of glacier variations in the studied time span (e.g. the Holocene). An ideal setting is one in which a single glacier has existed in the catchment throughout the Holocene, but has been so small that only the most sensitive sites have a continuous record of Holocene glacier activity. The area/altitude distribution of the glacier must be taken into account in this evaluation.

• The net mass balance of glaciers (and the ELA) in general depends on the regional distribution of temperature in the ablation season and winter precipitation as snow in the accumulation season. Local redistribution of (dry) snow by wind from exposed surfaces to leeward topographic depressions is in addition of great importance. On ice caps (plateau glaciers) with outlet glaciers in all aspects, the influence of wind can be neglected as the mean ELA will even out the deflation on the windward side and the additional accumulation on the leeward side for any snow-bearing wind direction. Hence, the *local topographic* temperature-precipitation-wind-ELA (TPW-ELA) of cirque glaciers may exist well below the *regional* temperature-precipitation-ELA (TP-ELA) of plateau glaciers (Fig. 3) (Dahl and Nesje, 1992; Dahl et al., 1997). Whether there is a plateau glacier or a cirque glacier in the catchment is thus of importance for the interpretation of the climatic factors influencing the reconstructed glacier activity/ELA.

• A number of downstream proglacial lakes and other sites suitable to document variations in GS/ELAs backwards in time is preferable to a single lake (see below). Without glacier(s) in the catchment the (proglacial) lakes should have a high organic production to differ from periods with glacier-meltwater-induced sedimentation, a requirement often fulfilled by lakes close to the present tree line. Representative nonglacial control lakes (Matthews and Karlén, 1992) should exist in the area.

• Proglacial lakes should be dammed by a rock sill and not by moraines, colluvial fans, rock avalanches, etc. Ideally, lakes with a flat bottom, gentle slopes and with no mixing of the water column to their base should be preferred to minimize post-depositional disturbance of the sediments. Hence, sites close to deltas and other unstable sedimentary environments where turbidites, snow avalanches, etc. commonly occur should be avoided. If possible, the lake bottom surrounding the coring site(s) should be flat in a radius of at least 150 m (Fig. 4).

• The residence time of water in a proglacial lake must be long enough to allow suspended sediments to settle, but short enough to allow some material in suspension to continue and settle in other lakes further downstream.

• To calibrate reconstructed variations in GS/ELAs based on proglacial sites, representative marginal moraines of known age must be found in the catchment (see below).

• Superficial sediments and active geomorphological processes (colluvial activity, floods, etc.) in the catchment may influence lake sedimentation, and must be taken into account.

• In general, ideal proglacial sites turn out to record simple systems where the topographic configuration isolates the glacier meltwater signal through natural filtering in a way that directly reflects GS/ELA.

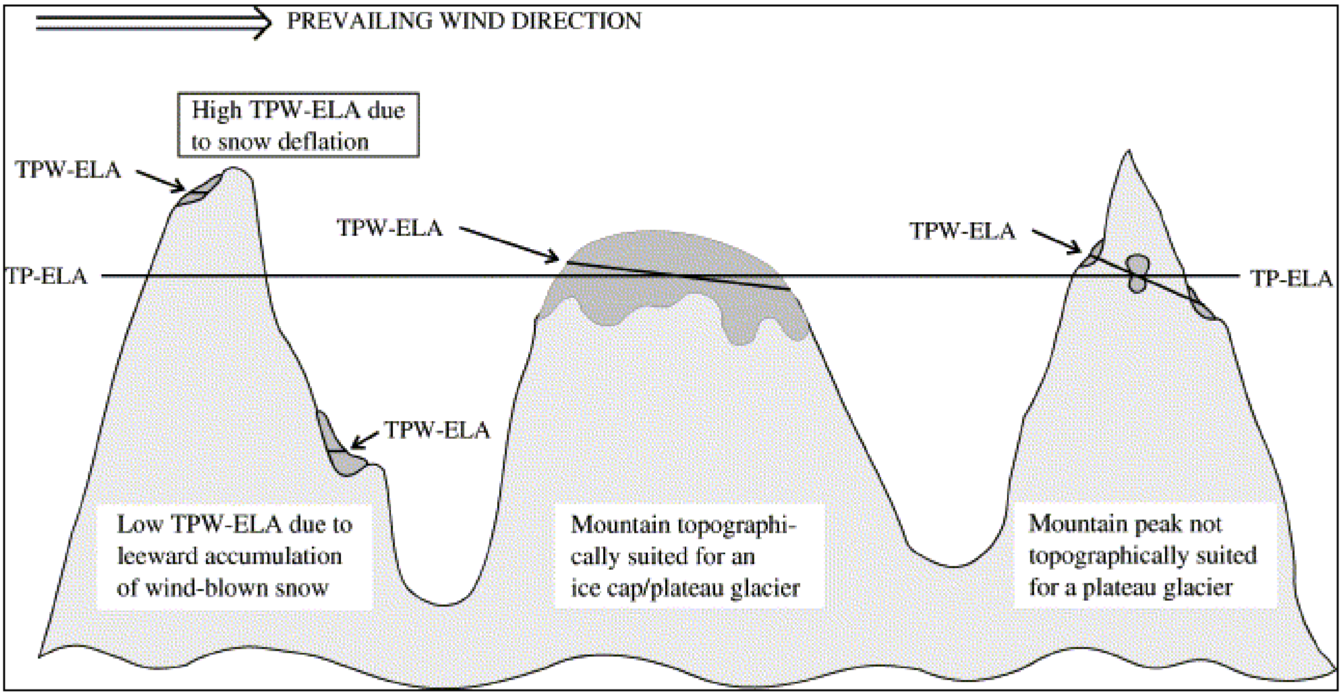

Fig. 3. Schematic examples showing the differences between the regional TP-ELA at plateau glaciers/ice caps and the local topography dependent TPW-ELA at cirque glaciers (Dahl and Nesje, 1992; Dahl et al., 1997).

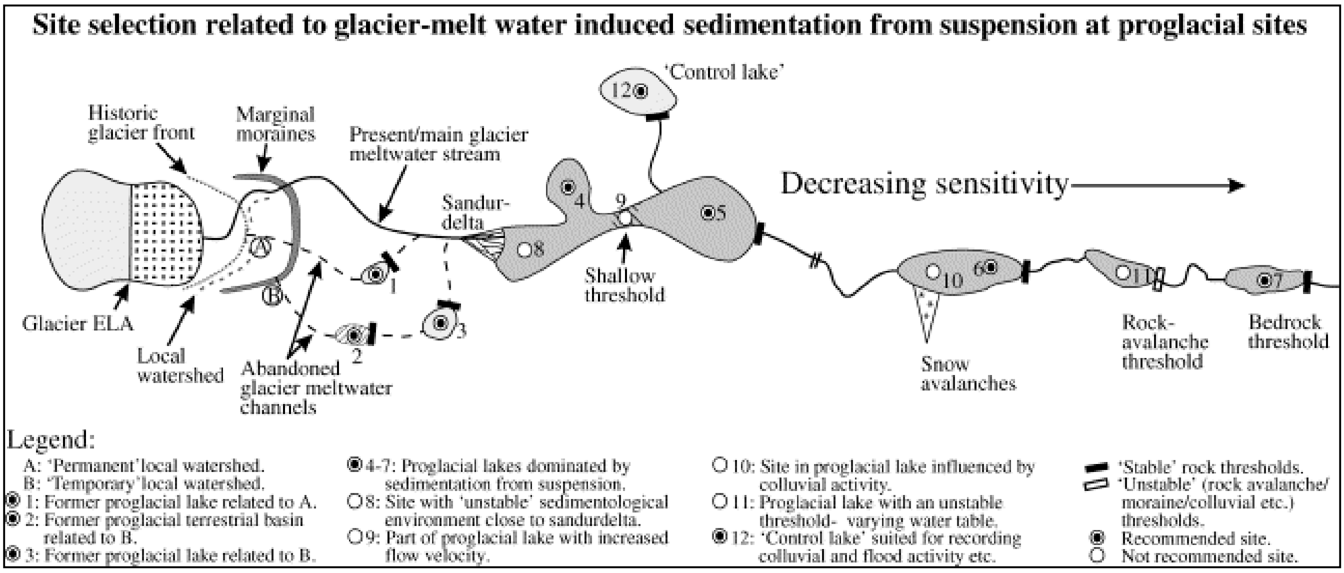

Fig. 4. Potential sites for investigating variations in glacier activity/ELA in a simple catchment with one glacier and a chain of proglacial lakes. Lacustrine and terrestrial sites related to both 'permanent' (bedrock) and 'temporal' (ice-marginal moraines) local watersheds, control lakes and various settings related to proglacial lakes are shown. Recommended coring sites are marked with partly filled circles, whereas secondary sites close to unstable sedimentary environments (normally not recommended) are marked with open circles. See legend and text for further details.

4. Reconstruction of former glacier ELAs

In addition to the maximum elevation of lateral moraines (MELM) (Fig. 4 and Fig. 5), the traditional ways to find former ELAs include the median elevation of glaciers (MEG), the toe-to-headwall ratio (THAR), accumulation area ratio (AAR), and the balance ratio method (see Nesje and Dahl, 2000, and references therein). In cases when only sparse remnants of marginal moraines are available, Dahl et al. (2002) introduced a new technique termed the Little Ice Age ratio to estimate the ELA of glacier advances predating the Little Ice Age maximum. In addition to defining the modern ELA of existing glaciers, these techniques are important for calibrating reconstructed ELAs based on proglacial sites.

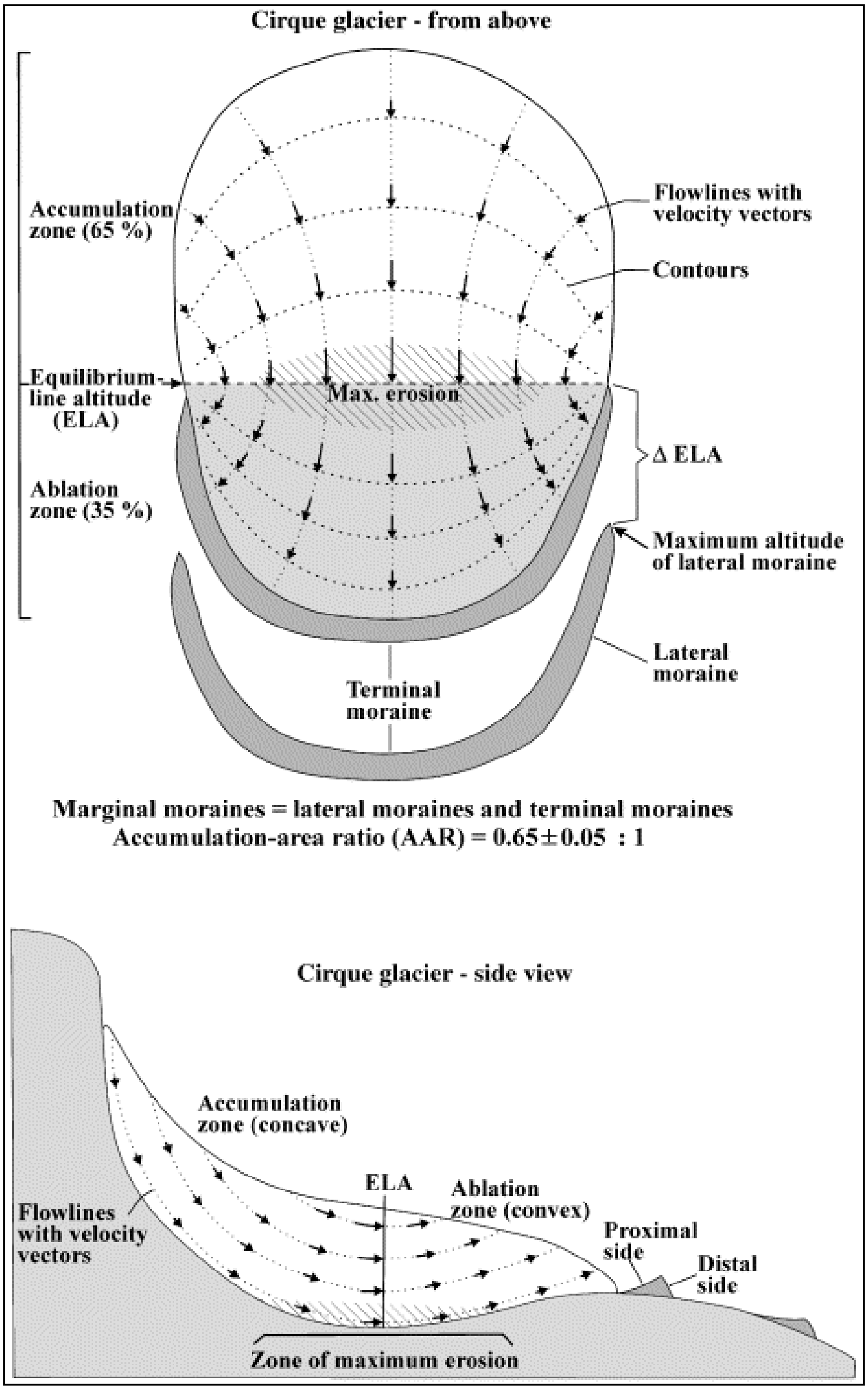

Fig. 5. Flow lines and contours on an idealized cirque glacier seen from above and in side view. Lateral moraines normally do not form above the steady-state ELA, and this can be used to estimate former ELAs. An AAR of 0.65:1 for a cirque glacier in climatic and dynamic steady state is shown. The maximum erosion related to the rotational movement beneath a cirque glacier is closely linked to the ELA, as both flow velocity (illustrated with vectors) and the maximum turnover of ice occur at or close to the steady-state ELA (modified from Lewis and Lewis; McCall and McCall).

4.1. Local watersheds

If combined with a proglacial lacustrine or terrestrial site, rerouting of glacial meltwater streams across local watersheds may give accurate estimates of former ELAs, if the extent of the corresponding glacier terminus is known from marginal moraines, historical records, air photographs, etc. (e.g. Dahl and Nesje, 1994; Dahl et al., 2002). Whenever the glacier is in an advanced position beyond the local watershed, glacier-meltwater-induced sediments may be deposited at the proglacial site, while only organic sediments accumulate when the glacier is behind the local watershed. This setting makes it possible to date whenever the glacier and the corresponding ELA are at, or close to, this on-off threshold.

Local watersheds consisting of ‘permanent’ bedrock thresholds are preferred to ensure that this on/off signal has existed throughout the Holocene. Such watersheds (especially inside the Little Ice Age glacier maximum) appear to be near, while rerouting of proglacial meltwater streams caused by ‘temporary’ marginal moraines are more common. Due to the sharp on-off signal related to local watersheds, reconstructed glacier termini are normally very accurate. If the reconstructed glacier front can be linked to a known ELA by

AAR, MELM, etc., reconstructed ELA variations related to local watersheds can be used to calibrate ELAs based on downstream proglacial sites (Fig. 4).

4.2. Chain of proglacial lakes

Based on data from nine Norwegian glaciers (Roland and Haakensen, 1985) there is a significant correlation (r=0.86) between glacier size/area and calculated sediment transport in proglacial meltwater streams. A similar relationship between the downstream transport distance of glacier-induced sediments in suspension and GS is suggested (Fig. 6), and consequently a chain of proglacial lakes can be used to record temporary variations in former glacier activity/ELAs. Small glaciers tend only to be recorded at the most sensitive sites, while larger glaciers in addition are recorded at sites further downstream.

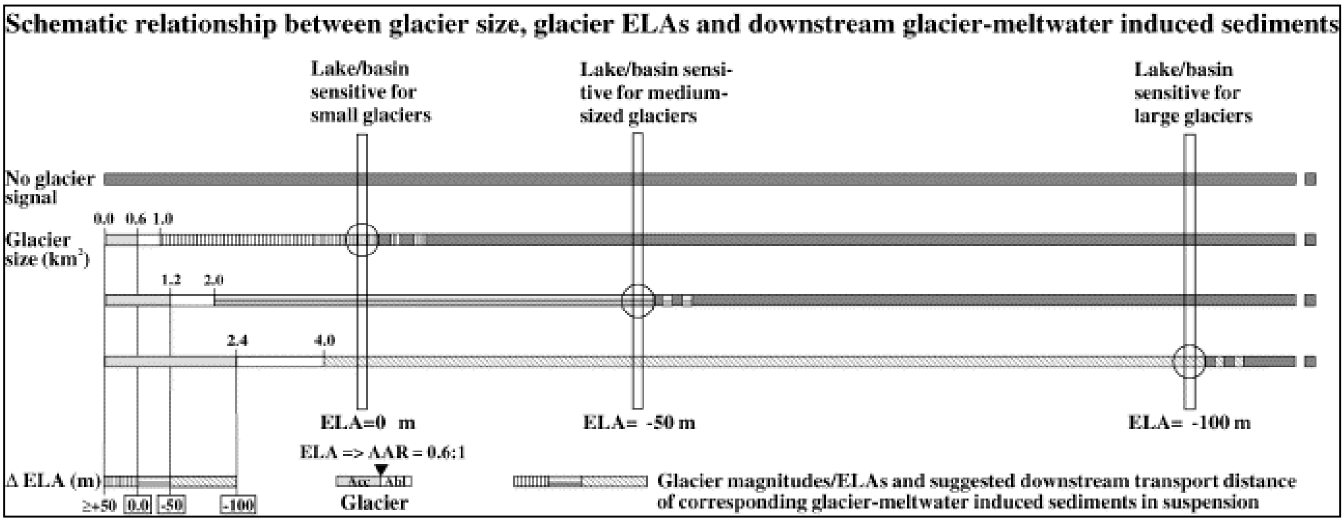

Fig. 6. Schematic relationship between GS (km^2) and SSD (km) in a simple catchment with one glacier and a chain of proglacial lakes. Primarily, the GS/SSD ratio is suggested to be a catchment specific ‘fixed’ relationship between GS and the downstream distance sediments from suspension can be recorded. In this example a tentative GS/SSD ratio of 1:4 has been used. GS is converted to an ELA estimate using the AAR method. To adjust for catchment dependent factors, however, independent proxies (e.g. lateral moraines, local watersheds, etc.) may be used to calibrate the amplitude of ELA fluctuations. See text for further explanation.

Depending on the size and response time, a lowering of the ELA results in a larger glacier when it has obtained climatic steady state. As a larger glacier/lower ELA leads to an increased meltwater discharge, a longer downstream distance of sediments in suspension is expected. Observations suggest that even a small increase in GS may correspond to an enlarged transport of sediments in suspension for several kilometres downstream (e.g. Dahl and Nesje, 1994). If this GS/sediments in suspension distance ratio (GS/SSD ratio) is known, records of glacier-induced sediments from a chain of proglacial lakes may give sensitive estimates of former variations in glacier magnitude.

The Finse Valley in central southern Norway is a simple catchment with a chain of proglacial lakes completely dominated by meltwater from the northern sector of the ice cap Hardangerjøkulen. Based on modern analogue studies during the ablation season (e.g. Fig. 1), well-dated stratigraphies from both proglacial lakes and basins related to local watersheds (Dahl and Nesje, 1994), and possibilities to establish fixed points for these sites which relate former glacier magnitudes to known ELAs (Dahl and Nesje, 1996), an approximate GS/SSD ratio of 1:4 for this catchment is suggested and used as a tentative example in Fig. 6. Any GS/SSD ratio is suggested to be catchment specific, however, and the ratio depends on a complex interaction between factors like nonglacial tributaries, relief of the river profile, water discharge, residence time of water in the proglacial lakes, etc.

GS given in square kilometres (km^2) is converted to an ELA estimate using the AAR method. To adjust for catchment dependent factors, the amplitude of the glacier/ELA signal in the proglacial lakes can be calibrated by the use of independent ELA observations of known age based on lateral moraines, local watersheds, etc. If the ELA and the corresponding GS/SSD ratio can be established for at least three fixed points spanning from small to large glaciers, a chain of proglacial lakes can be used to calculate continuous variations in former ELAs as schematically illustrated in Fig. 6. For small glaciers only the most sensitive proglacial lake closest to the glacier can record fluctuations in GS/ELA, while for large glaciers only the most distant proglacial lake is sensitive for variations in GS/ELA (see Fig. 2).

If the investigated chain of proglacial lakes has a GS/SSD ratio which allows all variations in GS within a given time span to be recorded, error bars for the estimated ELAs of less than ±50 m are suggested. Reconstructed ELAs must normally be adjusted for glacio-isostatic land uplift (e.g. Dahl and Nesje, 1996).

4.3. One-site approaches

Downstream of many glaciers, suitable proglacial sites are often lacking or scarce. Hence, in many cases a setting with only one proglacial lake is all that is available to investigate how such glaciers and the corresponding ELAs have fluctuated backwards in time. If a glacier exists in the catchment at present, various proxies can record whenever former glaciers existed by using 'the modern analogue principle'. With a multi-site approach these proxies can be calibrated against independent sites with different sensitivity to record variations in glacier magnitude/ELA. For one-site approaches, variations in glacier activity/ELAs depend on the interpretation and sensitivity of the available methods (Fig. 2). However, some of these methods may be sensitive to record variations in small glaciers, while others can be used to record fluctuations in larger glaciers.

5. Discussion

Effective rates of glacial erosion varies from 0.01 mm yr^{-1} for polar glaciers and thin temperate plateau glaciers on crystalline bedrock, to 0.1 mm yr^{-1} for temperate valley glaciers on resistant crystalline bedrock in Norway, to 1.0 mm yr^{-1} for small temperate glaciers on various bedrock types in the Swiss Alps, and to 10–100 mm yr^{-1} for large and temperate valley glaciers in the tectonically active mountain ranges of southeast Alaska (Hallet et al., 1996, and references therein). Hence, the link between variations in GS and the corresponding ELA based on proglacial lakes must be established for each glacier.

The bedrock beneath a glacier can be regarded as 'constant', whereas both temperature regime and thickness may vary with the size of the glacier. The temperature regime of a glacier also depends on air temperature and winter precipitation, and shifts from polar or polythermal to temperate may have taken place at the Younger Dryas/Holocene transition or from temperate to polythermal after the Holocene climatic optimum. Variations in the turnover time of ice in temperate glaciers may also have some influence on rates of effective glacial erosion.

The annual sediment transport along glacier meltwater streams normally exceeds by several orders of magnitude nonglacial streams with similar water discharge in Norway (e.g. Roland and Haakensen, 1985). This transport occurs as rolling, sliding and saltation along the channel bed, or in suspension. Some grains descending during saltation may be temporarily buoyed by upward movement in turbulent flow, and this condition can be described as incipient suspension. The weight of fine particles in true suspension is entirely supported by the upward pulses of flow generated by eddies (e.g. Summerfield, 1996). It is particles deposited from true suspension which make the ideal basis for using proglacial sites to reconstruct variations in glacier extent/ELA. Depending on the site and the competence of the meltwater stream, however, particles from incipient suspension are commonly found as coarser grains (coarse silt to sand) in sediments deposited at proglacial sites. For most proglacial sites, however, the glacier signal is found in fine- to medium silt (e.g. Leemann and Niessen, 1994; Matthews et al., 2000; Nesje et al., 2001). Hence, proglacial sites dominated by sedimentation from true suspension are preferred (Fig. 4).

In a study on the relationship between glacial activity and sediment production in the varved Hector Lake, Alberta in Canada, Leonard (1997) found that longterm variations (century to millenial duration) in sedimentation rate reflected changes in glacier extent on the same timescale. However, decadal-scale variability more complexly related to upstream ice extent is superimposed on the longterm changes. High sedimentation rates were associated with glacier maximum positions, or with transitional periods preceding or post-dating periods of maximum ice extent. The glacier-covered area in the catchment of Hector Lake has varied from 60% during the Little Ice Age to 40% at present, a coverage of glaciers four to six times higher than for the majority of similar investigations in southern Norway.

The first lake in a chain of proglacial lakes acts as a sediment trap for coarser sediments. If the first lake is covered by the glacier, this is reflected as a shift from a low-energy mode to a high-energy mode in the lacustrine sedimentation of the second proglacial lake (e.g. Nesje et al., 2001). As temporary ice-dammed lakes commonly occur along glacier margins both during advance and retreat, this may explain some of the difficulties in interpreting whether high sediment production is directly linked to glacier maximum positions or not.

In a multidisciplinary study, Snowball and Snowball recored proglacial lakes in the Kårsa valley in northern Sweden first investigated by Karl; Karl and Karl.

Based on different methodological approaches, Snowball and Sandgren (1996) found that following the last deglaciation, glaciers had existed in the catchment only for the last 3000 ^{14}C yr BP, a result which strongly contrasted the interpretation of Karl and Karl who had suggested several glacier advances throughout the entire Holocene. Based on this investigation, Snowball and Sandgren (1996) strongly argued against single-core (site) studies. They also argued that only features that are consistently reproducible and can be dated in spatially distributed cores should be interpreted in terms of glacier activity, environmental conditions and climate change. However, the problems of getting reproducible results can normally be solved by using proglacial lakes with a flat bottom.

Brauer et al. (2001) compared four sediment profiles from lakes Holzmaar and Meerfelder Maar in the Eifel region, Germany. Based on varve-dating and pollen profiles from the two lakes, former discrepancies between the two lakes were explained after detailed correlation. They concluded that even in small lakes like Holzmaar discrepancies of several hundred years may occur, and that a multi-core study on two lakes from the same region is necessary to detect errors in single-core studies on nonvarved sediments.

Multi-core/site approaches are therefore preferred (e.g. Snowball and Sandgren, 1996; Brauer et al., 2001). However, suitable proglacial sites are difficult to find in many regions, and in many cases none or very few sites are available. To minimize within lake variance and maximize between lake variance, basins distal from the inlet and/or the deepest part of the lake appear to give the best reproducable results when more than one core/site are taken into account. For one-site studies, only features that are consistently reproducible based on several independent proxies in two or more cores should be interpreted in terms of glacier variations and climate change. The principal coupling between various techniques/proxies and former glacier activity/ELAs is demonstrated in Fig. 2. Hence, for one-site approaches it is especially important that these principles are followed.

Church and Ryder (1972)defined the term ‘paraglacial’ as referring to "nonglacial processes that are directly conditioned by glaciation". The term has been widely used to describe the reworking of glacigenic sediments by colluvial processes and running water after the withdrawal of glacier ice, including the landforms and sediment accumulations produced by such processes (e.g. Ballantyne, 1995). Attributed to nonglacial activity, thin ($\leqslant$2 cm) minerogenic layers and less-regular layers composed of coarse, angular sand and gravel particles, are found in both glacial and nonglacial lakes with steep slopes in the catchment (Matthews and Karlén, 1992). The thin layers are suggested to result from precipitation-induced events, including debris flows (Østrem and Olsen, 1987; Jonasson, 1991), while the less-regular layers are interpreted as ice-rafted colluvial debris (e.g. Luckman, 1975).

Colluvial activity often occurs within a limited area and as short (hours to days) events. However, similar minerogenic layers in nonglacial control lakes (Matthews and Karlén, 1992) and multi-core/site approaches reflecting the same glacier may reveal the origin of a nonglacial layer. Due to the longevity of many glacier-induced events (several hundred years) compared to colluvial events, radiocarbon dates above and below the actual layer may in some cases disclose the depositional agent.

By using ‘ward sorting’ on grain-size distributions to establish cumulative platforms, ‘true’ glacial meltwater sediments may be separated from deposits originating from colluvial activity (Blott and Pye, 2001).

6. Summary and conclusions

Except for historical records and observed mass-balance records, knowledge of former variations in glacier activity/ELAs rely, directly or indirectly, on the maximum altitude of lateral moraines and on information from proglacial lacustrine and terrestrial sites. As lateral moraines only reflect shorter periods when the glaciers obtained steady state in advanced positions beyond later glacier advances, continuous Holocene variations in glacier activity/ELAs can only be obtained from proglacial sites beyond the Little Ice Age maximum.

In this paper, various approaches and techniques for reconstructing variations in former glacier activity/ELAs based on proglacial sites are evaluated, and criteria for site selection are discussed. The following conclusions and implications of systematic importance are proposed:

Records of glacier activity/ELAs obtained from proglacial sites are based on a conceptual model of glacier-meltwater-induced sedimentation in which the minerogenic (nonorganic) component of the sediments is related to the occurrence of a glacier in the catchment (Fig. 1) (e.g. Karlén, 1981; Leonard, 1985).

The principal coupling between various approaches and former glacier activity/ELAs is the same, and both possibilities and limitations are exemplified in Fig. 2. Problems in the interpretation and calibration of these parameters are primarily related to when the glacier was very small/melted away, or when it was so large that the used proxy lacked sensitivity to record variations in GS. However, the various approaches may complement each other.

Within the studied time span (e.g. the Holocene), the glaciated area in the catchment must be appropriate for recording the amplitude of variations in GS/ELA. The largest glacier in the catchment must also be classified (cirque glacier, plateau glacier, etc.) to understand better which climatic factors influence the local glacier activity/ELA (Fig. 3) (Dahl and Nesje, 1992; Dahl et al., 1997). Reconstructed ELAs must normally be adjusted for glacio-isostatic land uplift.

Catchments with a high number of proglacial lakes and other sites/features (local watersheds, lateral moraines, etc.) suitable to record variations in GS/ELAs are to be preferred (Fig. 4 and Fig. 5). Proglacial lakes should be dammed by a rock sill, and the shape of the lake basins should minimize post-depositional disturbance of the sediments. With no glaciers in the catchment, ‘proglacial’ lakes should have high organic production to increase the contrast, and the residence time of water in the proglacial lakes must allow both settling and further downstream transport of suspended sediments. Representative nonglacial control lakes should exist in the catchment (Matthews and Karlén, 1992), and geomorphological processes (colluvial activity, floods, etc.) which may influence on lake sedimentation must be taken into account.

Ideal proglacial sites turn out to record simple systems where the topographic conditions isolate the glacier meltwater signal through natural filtering in a way that directly reflects GS/ELA. The occurrence of representative ice-marginal moraines of known age in the catchment is crucial for the calibration of glacier activity/ELAs based on proglacial sites.

Combined with proglacial sites, rerouting of glacier meltwater across local watersheds may give detailed information concerning former glacier activity/ELAs. Due to the sharp on-off signal, reconstructed variations in GS/ELA related to local watersheds can be used to calibrate ELAs based on a chain of proglacial sites (Fig. 4) (e.g. Dahl and Nesje, 1994; Dahl et al., 2002).

A close relationship between GS and downstream transport distance of glacier-induced sedimentation from true suspension is suggested based on Roland and Haakensen (1985). As a consequence, small glaciers can only be recorded at the most sensitive sites, while larger glaciers in addition can be recorded further downstream. If this catchment specific GS/SSD ratio is known (Fig. 6), records of glacier-induced sediments from a chain of proglacial lakes may give continuous sensitive variations in glacier magnitude backwards in time. GS is converted to an ELA estimate using the AAR-method. Independent observations (lateral moraines, local watersheds, etc.) are used to calibrate the amplitude of ELA fluctuations for catchment dependent factors. If the investigated chain of proglacial lakes has a GS/SSD ratio which allows all variations in GS within a given time span to be recorded, error bars for the estimated ELAs may be less than ±50 m.

With a one-site approach, variations in glacier activity/ELAs depend on the interpretation and sensitivity of the used methods. Hence, to minimize within lake variance and maximize between lake variance, basins distal to the inlet and/or the deepest part of the lake appear to give the best reproducable results when more than one core is taken into account. For one-site studies, only features that are consistently reproducible based on several independent proxies in two or more cores should be interpreted in terms of glacier variations and climate change (e.g. Snowball and Sandgren, 1996; Brauer et al., 2001).

A critical factor for the use of both one-site approaches and a chain of proglacial lakes is the link between glacier advances and sediment production. Whether a longer transport length of sediments in suspension can be related to glacier maximum positions, or to periods preceding or post-dating periods of maximum ice extent (e.g. Leonard, 1997), is important for the interpretation of all proglacial sites, and must be further tested.

Comparison of reconstructions using approaches based on both a single proglacial lake and a chain of proglacial lakes for the same glacier is important for the development of reliable methods/techniques to reconstruct former glacier activity/ELAs. Hence, testing and improvement of relevant field and laboratory approaches must continue, and especially how various methods/techniques complement each other must be better understood.

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