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# Proglacial lakes: character, behaviour and geological importance

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ABSTRACT

Proglacial lakes are ubiquitous within the Quaternary record and can provide exceptional breadth and depth of palaeoenvironmental information. Present deglaciation is increasing the number and size of proglacial lakes around the world. This study provides a synthesis of knowledge on proglacial lake character and behaviour and critically evaluates the importance of proglacial lakes from a geological perspective. We show how 'ice-marginal' or 'ice-contact' lakes and other distal proglacial lakes can be distinguished from each other by geomorphological, sedimentological, chemical and biological characteristics. The key controls on proglacial lake geomorphology and sedimentology are outlined and discussed. Proglacial lakes can exacerbate mountain glacier and ice sheet margin ablation via mechanical and thermal stresses, but very large lakes can moderate summer air temperatures and relatively retard summer ice ablation. Proglacial lakes interrupt meltwater flux and are very efficient sediment traps. Hydrological routing and consequent geomorphological activity can be radically modified by sudden drainage of proglacial lakes and resultant glacial lake outburst floods; exceptionally large proglacial lake drainages affected global ocean circulation and global climate during the Quaternary. Overall, analyses of proglacial lakes can provide a valuable insight into (i) patterns, character and behaviour of mountain glaciers, ice sheets and glaciations, and (ii) the impacts of past, present and future deglaciation.



## 1. Introduction and rationale

This study provides a synthesis of knowledge on proglacial lakes with an emphasis on local, regional and global effects on geological systems. Proglacial lakes are masses of water impounded at the edge of a glacier or at the margin of an ice sheet. The term 'proglacial lake' has been used to refer to ice-contact or ice-marginal lakes, which are physically attached to an ice margin, as well as lakes detached from, or immediately beyond, a contemporary ice margin. In this paper, the term proglacial lake therefore includes all lakes that are or have been directly influenced by (i) a glacier ice margin or (ii) subaerial glacial meltwater.

Proglacial lakes are very significant within the Quaternary record. The character and behaviour of proglacial lakes is intrinsically linked to climate though the surface energy balance and to wider geological systems through glacier dynamics, glacial meltwater and sediment fluxes (e.g. Larsen and Miller, 2011). Proglacial lakes can affect the stability of ice-sheet margins and mountain glaciers and can disengage glacier behaviour from climatic perturbations. Proglacial lakes interrupt the delivery of meltwater and sediment to proglacial zones and ultimately to oceans. Sedimentation within proglacial lakes is an exceptionally important geochronological archive recording short-term inter-seasonal patterns, inter-annual patterns, and long-term patterns of glacier-derived meltwater fluctuation. Thus proglacial lake records are used by proxy to reconstruct glacier mass balance (e.g. Phillips et al., 1996; Larsen and Miller, 2011), although that can be highly variable between catchments and through time (e.g. Carrivick and Chase, 2011). In practical terms, knowledge of proglacial lakes has application in assessments of sites vulnerable to glacier outburst floods, aquatic ecosystem monitoring and hydro-electric power generation, for example. Therefore, it is now critically important to (i) better understand the Quaternary record by using recent quantitative studies of modern analogues, and (ii) assess the potential geological importance of the observed evolution and development of proglacial lakes around the world. The major motivations for this study are that;

(i) Proglacial lakes are pervasive within worldwide geological records of Quaternary deglaciation (e.g. Teller, 2001; Jansson, 2003; Mangerud et al., 2004; Larsen et al., 2006a,b; Livingstone et al., 2010; Fiore et al., 2011; Murton and

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Murton, 2012) and in most cases offer exceptional breadth and depth of palaeo-environmental information (e.g. Thomas and Briner, 2009).

(ii) Present deglaciation is producing an increased number and size of proglacial lakes around the world; for example, as recently documented in the European Alps (e.g. Paul et al., 2007), the Caucasus (e.g. Stokes et al., 2007), Iceland (e.g. Schomacker, 2010), South America (e.g. Loriaux and Casassa, 2012; Thompson et al., 2011) and across the Himalaya (e.g. Gardelle et al., 2011) and specifically within the Mt Everest region (Tartari et al., 2008), in Bhutan (Komori, 2008) and Tibet (Chen et al., 2007; Wang et al., 2011). It is very important to understand the effects that these lakes could have on modern and future geological and environmental systems.

(iii) Glacial lake outburst floods (GLOFS), which are a type of jökulhlaup, are ubiquitous within the Quaternary record of deglaciation (e.g. Baker, 2007), and also have a modern geological imprint and are modern natural hazards.

The aims of this study are to provide a review of the character and behaviour of proglacial lakes, emphasising recent developments in knowledge and understanding and critically evaluating the importance of proglacial lakes from a geological perspective. Specifically, we focus on; (i) recent advances in understanding the formation and evolution of proglacial lakes; (ii) criteria for distinguishing proglacial lakes from other freshwater lakes, from marine glacier margins and from subglacial lakes in the Quaternary record; and (iii) identification of the linkages between proglacial lakes and glacier dynamics, meltwater and sediment fluxes and weather and climate, as determined from the Quaternary record and from modern measurements.

## 2. Proglacial lake character and behaviour

In this section, key attributes of proglacial lakes that shape their geological significance are discussed. Consideration is given to past and present locations and distributions of proglacial lakes before a discussion of controls on proglacial lake formation and evolution. Physical characteristics of proglacial lakes are subsequently described with emphasis on key geomorphological and sedimentary characteristics that are of use for (i) determining past glacial and hence palaeo-environmental patterns, and (ii) distinguishing proglacial lakes from other freshwater lakes, from marine glacier margins and from subglacial lakes in the Quaternary record. Whilst proglacial lakes occur worldwide, we note that the literature on proglacial lakes is dominated by studies within (temperate) high mountain and high latitude regions.

### *2.1. Location and distribution of proglacial lakes*

Proglacial lakes can be situated in front and at the sides of mountain glaciers, at the front and sides of ice sheet outlet glaciers and at the edge of nunataks and are most commonly dammed by ice, bedrock, moraine debris or landslide debris (Fig. 1). Less commonly, proglacial lakes can be dammed by other sediments; for example as a glacier retreats and thins behind the ice-contact slope of a glaciofluvial fan or apron (Carrivick and Russell, 2013). Previous reviews have compiled data on natural dams (e.g. Costa and Schuster, 1988) and have discussed the formation and catastrophic drainage of ice-dammed lakes (e.g. Tweed and Russell, 1999), moraine-dammed lakes (e.g. Richardson and Reynolds, 2000) and landslide dams (e.g. Korup, 2002). Proglacial lakes exist in all currently glaciated regions of the world and the legacy of proglacial lakes is frequently evident in formerly glaciated areas. Table 1 provides examples of modern proglacial lakes from around the world. Table 2 provides examples of major palaeo-proglacial lakes, particularly those lakes associated with Late Pleistocene ice sheet deglaciation from which sudden drainage generated some of the largest floods on Earth and affected ocean currents and offshore sediment fluxes.

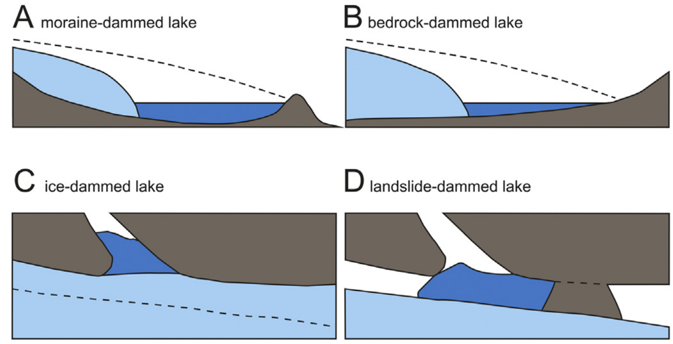


**Fig. 1.** Proglacial lake evolution in response to ice advance and retreat, where dashed line indicates a previous ice margin, or slope margin in part D. Note that part A and B are in longitudinal view, and parts C and D are in plan view. No spatial or temporal scale is implied.

### *2.2. Proglacial lake formation*

Proglacial lakes can be impounded by ice, moraine, landslide debris or bedrock (Costa and Schuster, 1988). The formation, evolution and persistence of proglacial lakes are strongly linked to glacier dynamics and the nature of the surrounding environment. There are clear associations between both of these factors and changing climatic conditions, but factors independent of climate can influence proglacial lake behaviour. The type of dam has implications for lake character, lake evolution and lake drainage. Failure or overtopping of the impounding material frequently leads to glacier lake outburst floods (GLOFS) or jökulhlaups (e.g. Walder and Costa, 1996; Tweed and Russell, 1999; Clague and Evans, 2000; Richardson and Reynolds, 2000; Nayar, 2009), which can be powerful agents of landscape change through erosion and sediment deposition (e.g. Carling, 1996; Carling et al., 2002; Carrivick et al., 2004a,b, 2007; Alho et al., 2005; Carrivick and Twigg, 2005; Russell et al., 2006; Carrivick, 2007).

Formation of ice-dammed lakes is a consequence of local topography and favourable hydraulic pressure gradients (Tweed

**Table 1**
Selected examples of studies on modern proglacial lakes.

| Region | Selected recent references |
|---|---|
| Greenland | Russell et al., 1990; Hasholt, 1993; Hasholt et al., 2000 |
| Iceland | Roberts et al., 2005; Schomacker, 2010 |
| European Alps | Haeberli et al., 2001; Huggel et al., 2002; Huss et al., 2007 |
| Tibetan Plateau | Richardson and Reynolds, 2000; Chen et al., 2007; Yao et al., 2010; Wang et al., 2011 |
| Himalaya | Fujita et al., 2009 |
| Alaska | Fleisher et al., 2003; Loso et al., 2004; Walder et al., 2005; Josberger et al., 2010 |
| South America | Harrison et al., 2006; Pasquini et al., 2008; Thompson et al., 2011 |
| Caucasus Mountains, Russia | Stokes et al., 2007 |
| New Zealand | Hicks et al., 1990; Kirkbride, 1993; Hochstein et al., 1998 |
| Norway | Liermann et al., 2012 |
| Canada | Lewis et al., 2002; Lamoureux and Gilbert, 2004 |