The morphology of supraglacial lake ogives

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ABSTRACT. Supraglacial lakes on grounded regions of the Greenland and Antarctic ice sheets sometimes produce 'lake ogives' or banded structures that sweep downstream from the lakes. Using a variety of remote-sensing data, we demonstrate that lake ogives originate from supraglacial lakes that form each year in the same bedrock-fixed location near the equilibrium-line altitude. As the ice flows underneath one of these lakes, an 'image' of the lake is imprinted on the ice surface both by summer-season ablation and by superimposed ice (lake ice) formation. Ogives associated with a lake are sequenced in time, with the downstream ogives being the oldest, and with spatial separation equal to the local annual ice displacement. In addition, lake ogives can have decimeter- to meter-scale topographic relief, much like wave ogives that form below icefalls on alpine glaciers. Our observations highlight the fact that lake ogives, and other related surface features, are a consequence of hydrological processes in a bedrock-fixed reference frame. These features should arise naturally from physically based thermodynamic models of supraglacial water transport, and thus they may serve as fiducial features that help to test the performance of such models.

1. INTRODUCTION

Ogive is a term used in glaciology to denote arch-like bands or waves on the surface of a glacier (BGS, 1953), often occurring immediately downstream of an icefall (e.g. Nye, 1958; King and others 1961; Posamentier, 1978; Waddington, 1986). Echelmeyer and others (1991) used this term to describe visibly distinct bands found downstream of some supraglacial lakes near Jakobshavn Isbræ, Greenland. Examples of supraglacial lakes in Greenland that have ogives are shown in Figures 1 and 2 (examples from Antarctica are shown in the supplemental online material, available at www.igsoc.org/hyperlink/). Lake ogives likely owe their alternating bands of surface color to variations in snow cover, superimposed ice characteristics (e.g. ice dust or bubble content) and/or surface dust concentration that extends out of an ephemeral lake and into a larger topographic basin. We use the term 'ephemeral lake' to designate the typically narrow sub-basin in the surface that contains standing meltwater during some portion of the year. Ephemeral lakes are often contained within larger surface topography basins that do not completely fill with water during the melt season. The narrowness of ephemeral lakes refers to the fact that they are often much shorter in span in the direction of ice-sheet flow than in the transverse direction. By superimposed ice, we refer to both traditional superimposed ice and ice that forms within surface lakes during winter. The lakes that produce ogives typically have a crescentic plan-view geometry. In a study of supraglacial hydrology, Lampkin (2011) found that lakes possessing this crescentic plan-view geometry are exclusively found at high elevation (>1400 m a.s.l.) and have low water volumes. We build on the high-elevation, low-water-volume setting identified by Lampkin (2011) by showing that the lakes in this setting are also more likely to be a source of lake ogives.

In a very brief initial description of lake ogives, Echelmeyer and others (1991) speculated that the ogives are a consequence of melting and freezing within a lake basin that has a bedrock-fixed location. The alternating melting and freezing within the basin was suggested to create alternating colors on the ice suface. Furthermore, ogive spacing was found to be in agreement with surveyed measurements of mean annual ice displacement. Here we expand on the observations of Echelmeyer and others (1991) by using several datasets that were not available at the time of their initial study. These new data allow us to further test the hypothesis proposed by Echelmeyer and others (1991) to explain lake-ogive creation and to discuss lake ogives in the wider context of ice-sheet topography and supraglacial water transport.

We are particularly interested in using lake-ogive morphology as a fiducial reference feature within the broader context of supraglacial hydrology, because lake-ogive morphology incorporates a smaller number of processes active in the ablation zone without requiring consideration of complex mass loss from spillover or moulin drainage. Recent studies (Clason and others, 2012; Leeson and others, 2012) of the ablation zone have modeled the evolution of supraglacial lakes with complex dynamics (e.g. filling, spillover and drainage through moulin), but ice-flow dynamics and accurate thermodynamic parameterizations differentiating bare ice ablation from lake-bottom ablation are missing. We propose that a reasonable way to assess these deficiencies in such models may lie in thinking about less complex lakes that neither spill over nor drain by moulins, such as those that produce lake ogives. Supraglacial lakes that produce lake ogives represent an end-member in the spectrum of supraglacial lakes in which draining or spilling over sills and through moulins, respectively, is absent. Instead, accumulated meltwater during the melt season is converted back to ice. While perhaps less interesting in this regard, we think that lakes with ogives represent the earliest stage in the evolution of a supraglacial lake. These nascent lakes form near the equilibrium line and are only slightly more complex than what would exist if the surface depression containing them were entirely empty. It is important to understand what happens in a simple lake, such as one that produces lake ogives, before proceeding to understand what happens in lakes that do drain through

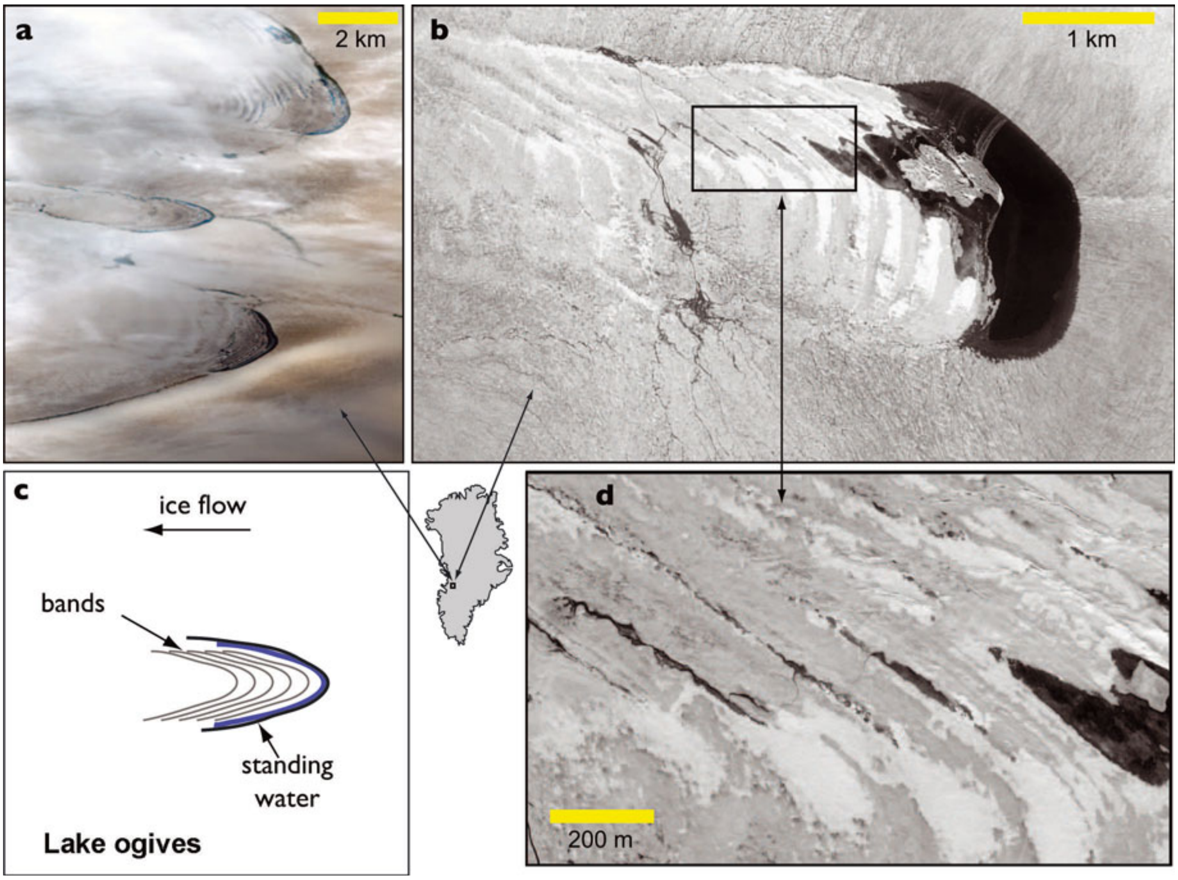

Fig. 1. Supraglacial lakes displaying ogives on the Greenland ice sheet. (a) Lakes with sequences of arch-like bands extending downstream (DigitalGlobe Inc. browse image, ~10 km wide, acquired 3 June 2010). (b) Close-up view of single lake with ogives (DigitalGlobe Inc. image, ~6 km wide, acquired 15 August 2009). (c) Subscene of (b) showing that banded structures are associated with subtle topography changes (denoted by organization of meltwater streams), superimposed ice characteristics and snowdrift. (d) Interpretive sketch of lake-ogive features. Imagery provided by the US National Geospatial-Intelligence Agency (NGA) Commercial Imagery Program. Copyright 2009 DigitalGlobe, Inc. See the supplementary online material for images of lake ogives in Antarctica and for time-lapse animations made from Landsat 7 imagery.

moulins, or lakes that interact with the surrounding ice surface. A desire to develop this understanding is our primary motivation. In this paper, we first introduce the lake-ogive morphology and explain the phenomenon. We then connect the morphology to the rest of the hydrologic phenomena of an ice sheet and indicate how lake ogives can be fiducial features that may be useful for testing the performance of numerical models of ice-sheet hydrology.

2. OBSERVATIONS

Numerous examples of lake ogives can be found in satellite imagery of Greenland and Antarctica. However, due to the greater prevalence of lake ogives in Greenland compared to Antarctica, we restrict our analysis to Greenland. We compiled data for 26 ogived lakes in Greenland (Table S1 in the supplemental online material). These lakes were identified by sequentially browsing Landsat images for lakes with banded structures that were visible for several years. We focused primarily on the region around Jakobshavn Isbræ because of the large number of available images, complementary airborne remote-sensing datasets and abundance of supraglacial lakes. Although our catalogue of ogived lakes is not exhaustive, it is enough to demonstrate that the basins in which ogived lakes form (1) are stationary in a bedrock-fixed reference frame and are not moving with the ice (Section 2.1); (2) are found immediately downstream of relatively steep surface slopes in locations near the equilibrium-line altitude (ELA) (Sections 2.2 and 2.3); and (3) have bands that are spaced by the annual ice displacement (Section 2.4).

2.1. Lake location

The majority of studies of supraglacial lakes on the Greenland ice sheet either suggest (e.g. Echelmeyer and others, 1991; Jezek and others, 1993) or assume (e.g. Box and Ski, 2007; Sundal and others, 2009; Selmes and others, 2011) that their position is fixed within the bedrock reference frame. Below, we demonstrate that all ogive-forming lakes in our catalogue have geographically fixed positions from 2000 to 2010.

Using clear-sky Landsat 7 imagery, we select the image of each ogived lake that shows the largest areal extent of standing water for each of the 11 years in our catalogue. However, due to the low temporal resolution of Landsat 7, we cannot confirm that this areal extent is the largest extent during a particular year. We choose this dataset for its long history and adequate spatial resolution (15 m). Typically, standing water is most widespread in late July or early August. For each of these images, we delineate a polygon representing the area of standing water. We then stack the collection of yearly polygons and calculate the number of

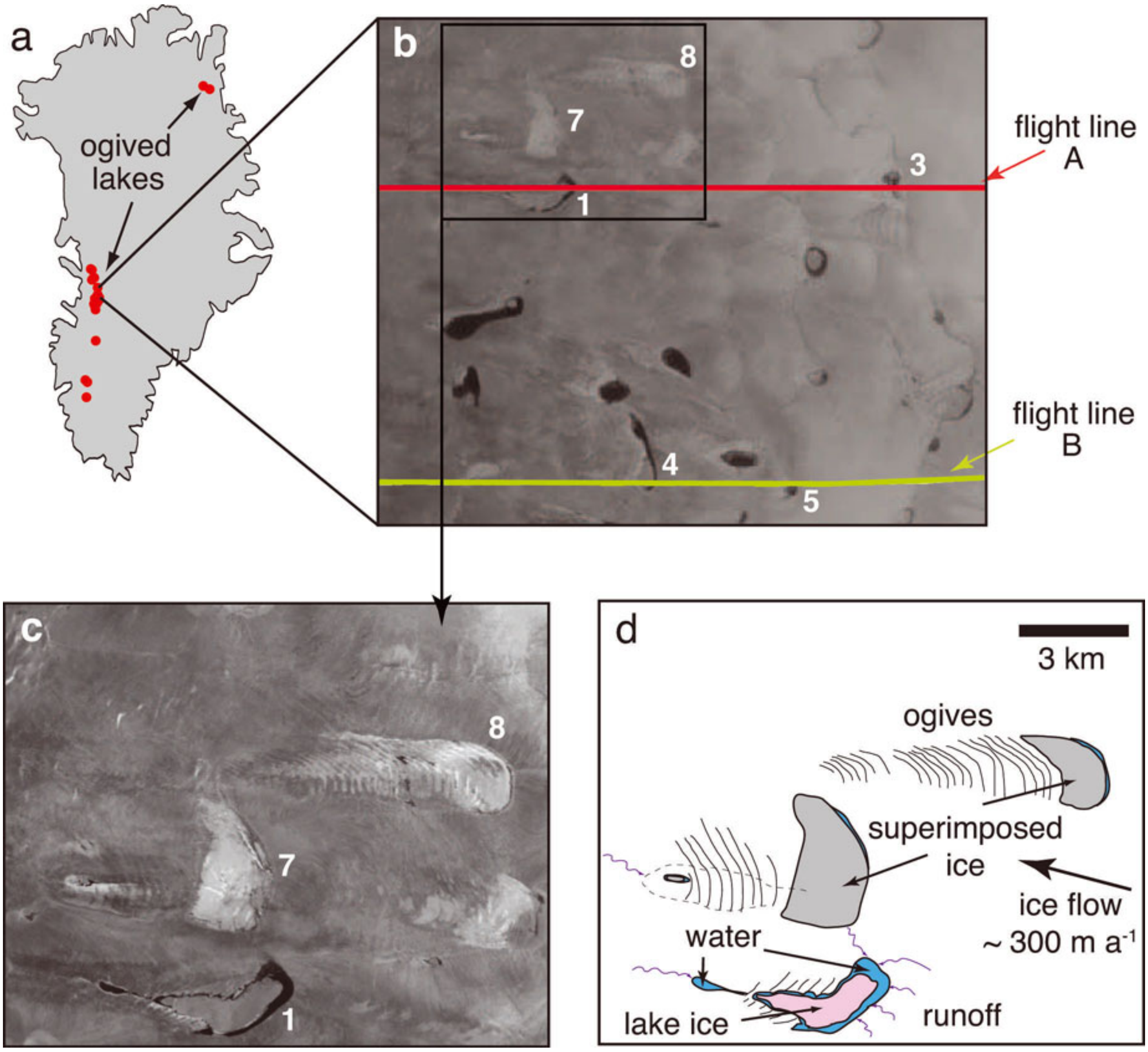

Fig. 2. Lakes with ogives investigated in this study. (a) Locations of 26 study lakes. (b) Satellite Pour l'Observation de la Terre (SPOT5) image from 2 August 2008 (SPIRIT: SPOT5 stereoscopic survey of Polar Ice: Reference Images and Topographies program of Centre National d'Etudes Spatiales, France), with lakes numbered as in subsequent figures and in the supplementary online material. Flight lines A and B refer to NASA ATM and CReSIS data displayed in Figure 4. Lakes 2 and 6 are not shown here, but do appear in Figures 3 and 7, respectively. Lakes 1 and 7 are the lakes studied by Echelmeyer and others (1991) (see their fig. 10a). Lake 8 is also shown in Figure 1b. (c) Close-up of (b). (d) Interpretive sketch of the SPOT5 image.

overlapping polygons at uniformly gridded points within the basin domain. The end result, shown in Figure 3, is a map of the persistence of standing water from year to year within each basin. The most notable attribute of Figure 3 is that standing water occurs for all 11 years at a fixed geographic location at the upstream end of the lake basin. This position remains fixed even though the ice flow has displaced the surface of the ice sheet by ~3 km during the same 11 years. Furthermore, we note that four lake basins in our dataset are visible in the same location in a 1985 aerial photomosaic (Motyka and others, 2010); this means that the positions of these lake basins have not changed during the past 25 years.

2.2. Surface and bedrock topography

We use data from NASA's Airborne Topographic Mapper (ATM; Krabill and Thomas, 2010), a digital elevation model (DEM) from Satellite Pour l'Observation de la Terre (SPOT5) and processed ice-penetrating radar data from the Center for Remote Sensing of Ice Sheets (CReSIS) to examine the ice-sheet surface and bedrock topography near the ogived lakes. Data from ATM have a spatial resolution of 10 m and a vertical resolution of ±0.3 m. The ATM flight lines were chosen because they crossed ogived lakes in the direction parallel to ice flow. The SPOT5 DEM is on a 40 m × 40 m grid with a 5 m along-track resolution and a 10 m cross-track resolution. We use this DEM for its availability and coverage. These flight lines and the SPOT5 DEM (Figs 4 and 5) indicate that the ogived lakes form (1) in depressions immediately downstream of relatively steep ramparts in the surface topography, and (2) at elevations where the ice-sheet surface slope is otherwise relatively small. Furthermore, the amplitude of the ogive undulations is on the order of decimeters. These observations indicate that lake ogives contain a topographic component (see Fig. 4b) and are not simply a visible color variation as was previously speculated (Echelmeyer and others, 1991).

2.3. Environmental conditions

We estimate the elevation of the 26 lakes in our catalogue by interpolating between gridpoints in a DEM of the Greenland

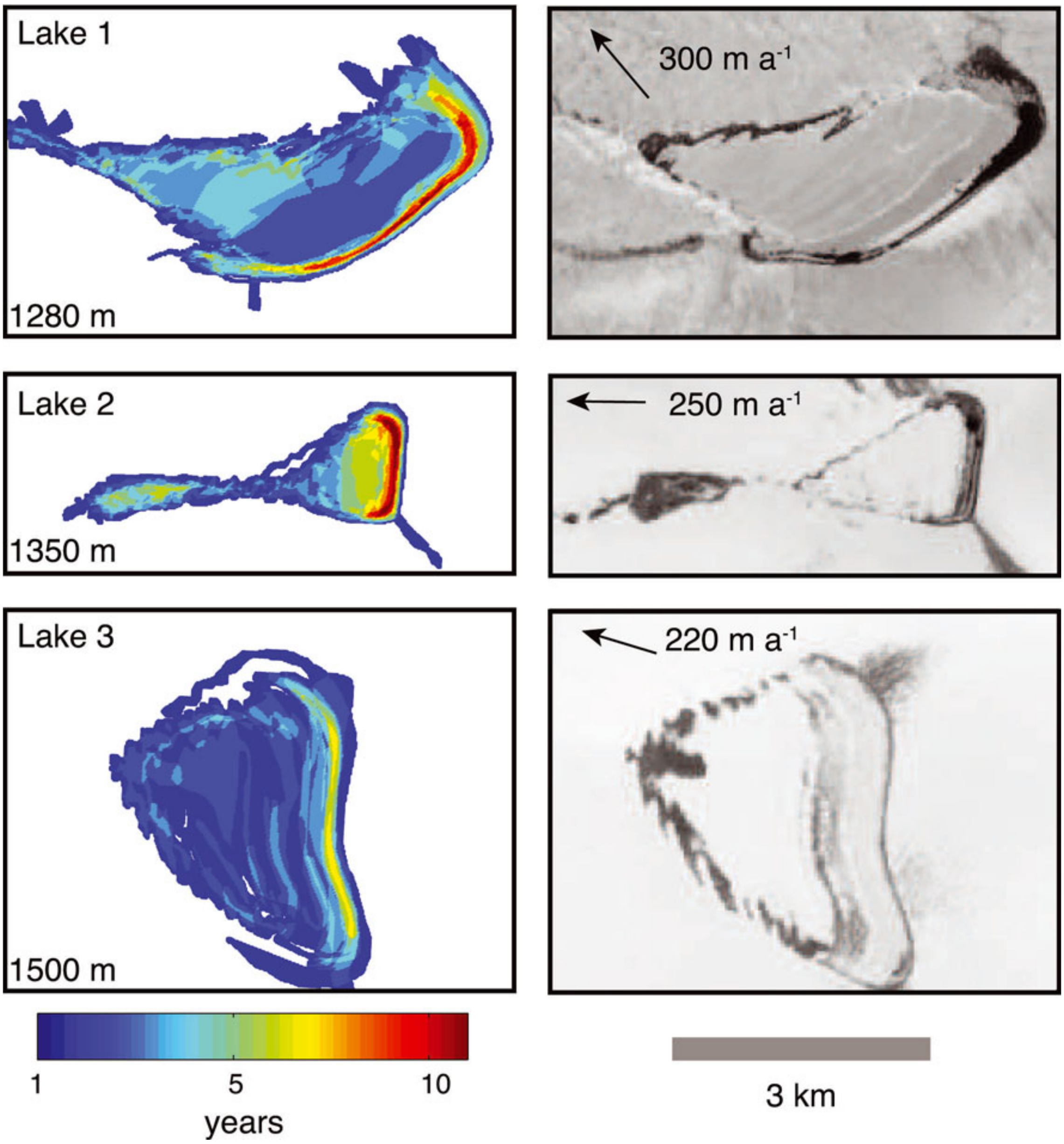

Fig. 3. Persistence of lake location within the bedrock-fixed reference frame. Left panels denote the number of years that standing water is visible in the geographically fixed (bedrock-fixed) location, with red indicating where standing water (filled lake) was visible for all 11 years (2000–10) for which Landsat 7 imagery was analyzed. Lake number is shown in upper part of box; elevation (m) is shown in lower part of box. Right panels show Landsat 7 imagery of the lakes (from 5 August 2000) with ice flow directions and speed (Joughin and others, 2008, 2010).

ice sheet with nominal 1 km spacing (Bamber and others, 2001; Layberry and Bamber, 2001). The lake elevations vary with latitude (Fig. 6) in a manner that closely approximates the latitudinal variation of the ELA over the Greenland ice sheet (Zwally and Giovinetto, 2001; Van de Wal and others, 2005). While we see ogived lakes above the estimated regional ELA, we do not know if this result is significant, as the ELA was computed from several sparsely scattered data points and demonstrates substantial interannual variability. More importantly, we interpret the correspondence of the elevation of ogived lakes with the regional ELA to be a demonstration that lake ogives are restricted to environmental conditions found in the vicinity of the ELA.

2.4. Annual ice displacement

We find that lake-ogive bands are, in general, separated by a distance equal to the annual ice motion as first observed by Echelmeyer and others (1991) (Fig. 2; Joughin and others, 2008, 2010); however, we additionally demonstrate, through successive Landsat imagery, that the ogives move down-glacier out of the lake basin (Video S1) at a rate equal to the surface ice velocity (Fig. 7). There is a subtle distinction here that is quite important. The video imagery provides evidence that water collects in these basins, is not drained but is refrozen into an annual ogive band of superimposed lake ice within a fixed basin, and then this ogive band advects out of the basin down-glacier. The previous observations (Echelmeyer and others, 1991) did not contain the temporal information necessary to demonstrate that the lake ogives were mobile features or that they were direct consequences of meltwater accumulation within the basin.

We can now confirm the hypothesis for lake ogives proposed by Echelmeyer and others (1991) by sampling repeat imagery for several lakes and comparing against

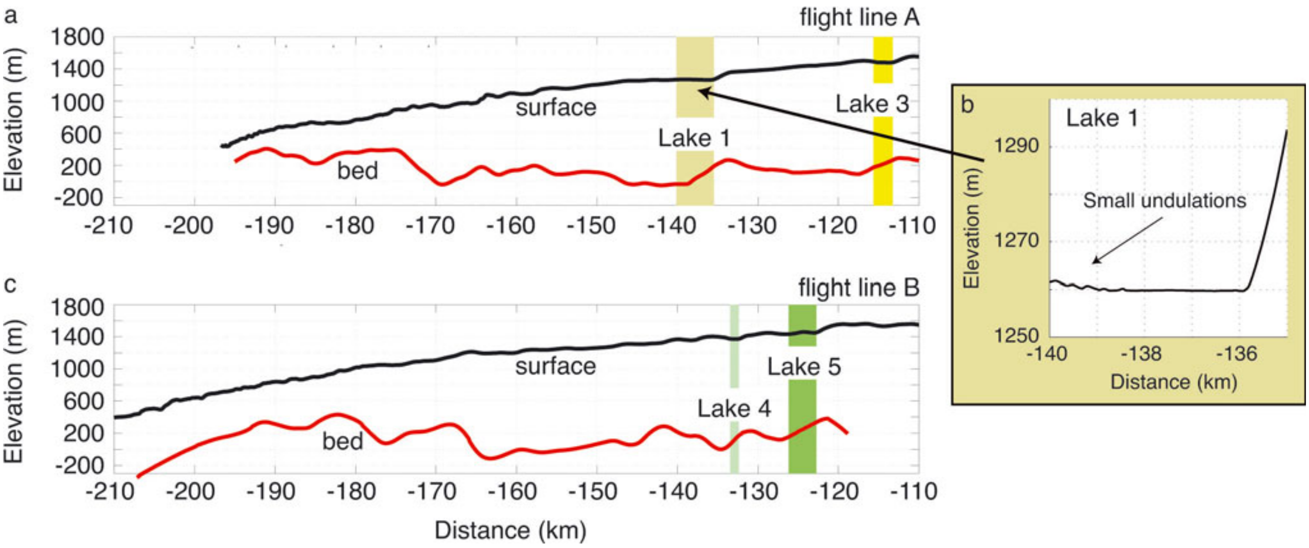

Fig. 4. (a, c) Flight lines A and B, respectively, indicated in Figure 2b. Surface (black line) and basal (red line) topography on along-flow transects that cross lakes with ogives. (b) Darkened panel shows enlarged surface topography at Lake 1. Surface topography is from NASA ATM data. Bedrock topography from the CReSIS multichannel coherent-radar depth sounder was smoothed with 1 km averaging window.

interferometric synthetic aperture radar (InSAR) velocity measurements. In Figure 7, we present Landsat pixel intensities (uncorrected digital numbers from the image data) for a single lake over a ~150 m wide swath that is parallel to the ice-flow direction. The pixel intensities were averaged across the swath, filtered with a 100–1000 m bandpass filter and normalized (to adjust for seasonal variations in sunlight and albedo). The filter was designed to remove long-wavelength oscillations in surface topography and short-wavelength oscillations due to small-scale surface roughness. The results are plotted as a series of waveforms, with peaks and troughs representing areas of high and low relative (uncorrected) pixel intensity, respectively. Variations in the wave amplitudes are not a measure of ogive growth or decay, but are simply an effect of the normalization of surface albedo in the data plotted. The ogives are found to advect down-glacier at a rate of ~230 m a^{-1}, in good agreement with satellite-derived velocities of the region (245 m a^{-1}; Joughin and others, 2008, 2010), whereas the up-glacier lake forming the ogives remains fixed.

3. DISCUSSION

The present examination of lake ogives on the Greenland ice sheet (and on the Antarctic ice sheet, as shown in the supplemental online material) serves to confirm and extend the lake-ogive formation hypothesis proposed over two decades ago by Echelmeyer and others (1991). Our analysis of remote-sensing data (both from satellites and airborne platforms) demonstrates their origin as a consequence of seasonal lakes on ice-sheet surfaces that are located in a bedrock-fixed basin through which the surface ice flows. Here we consider the conditions that are likely responsible for the presence, as well as the absence, of lake ogives and

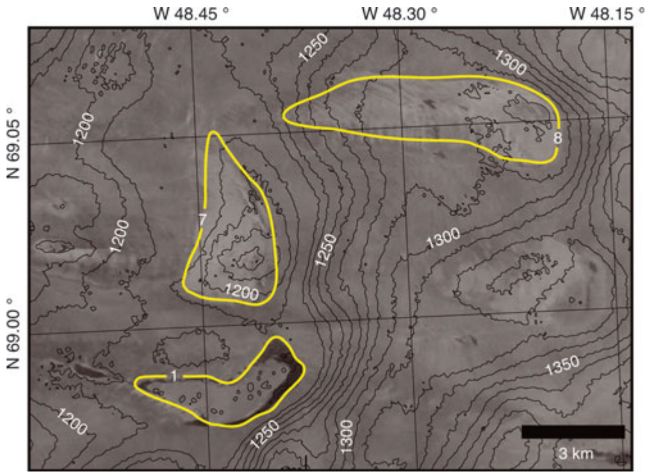

Fig. 5. Digital elevation model (DEM) produced from SPOT5 imagery acquired on 2 August 2008, with 10 m contours in black. Lakes 1, 7 and 8 are outlined, and SPOT5 visual imagery is also shown. These lakes are located in the same geographic positions in aerial photos taken in 1985 (Motyka and others, 2010).

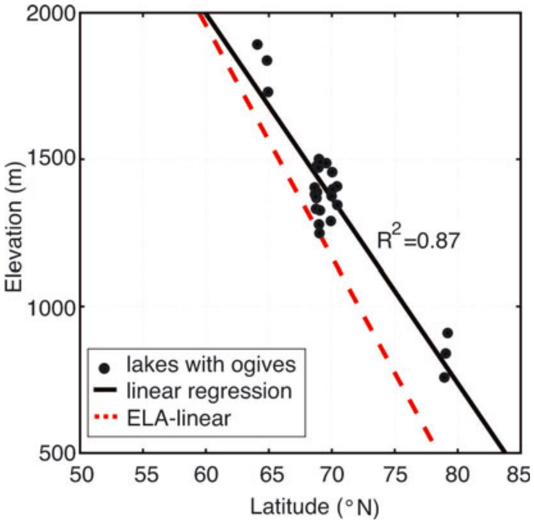

Fig. 6. Lake elevation vs latitude for 26 lakes with ogives (black dots). The linear regression (black line) is similar to the linear relation recommended for ELA variation with latitude by Zwally and Giovinetto (2001) (see also Van de Wal and others, 2005).

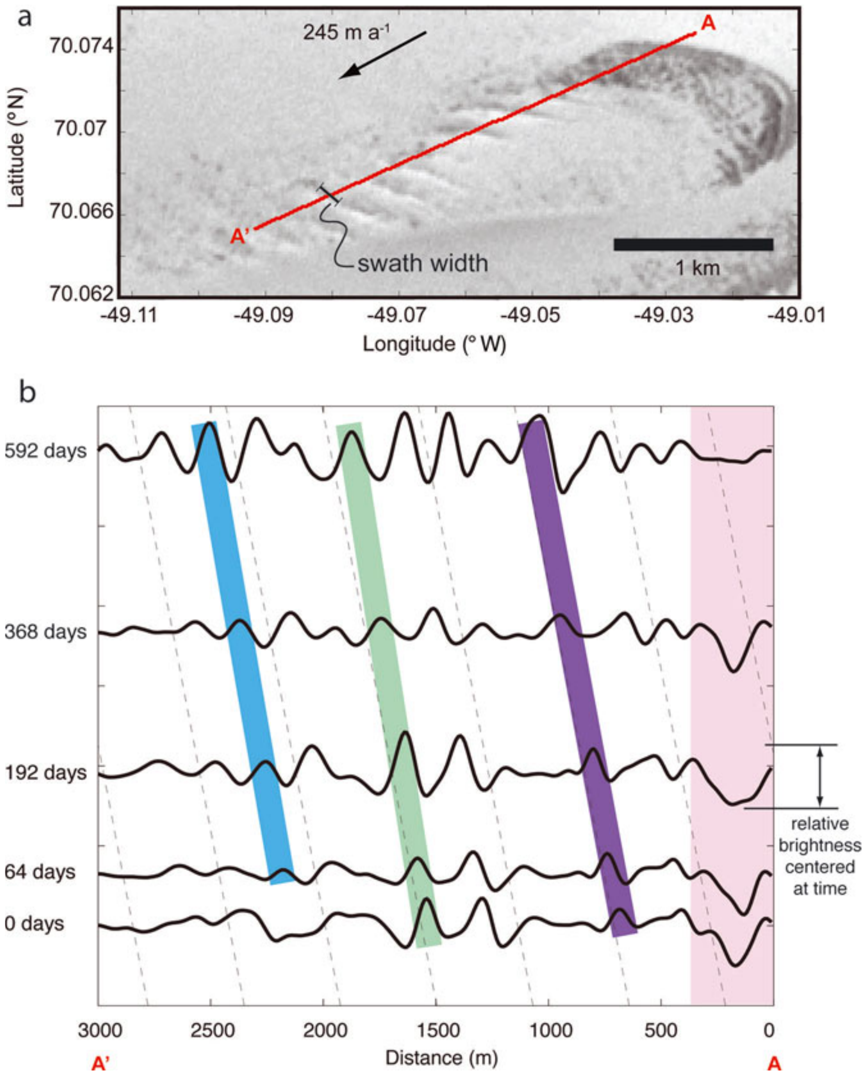

Fig. 7. (a) Landsat 7 image of Lake 6 with the transect, A–A′, along which ogive features were tracked. Along the transect we measured an average of relative pixel brightness calculated for a 150 m wide swath centered on the transect. (b) Brightness profiles along the longitudinal section A–A′ at five points in time. Mean vertical position of the longitudinal sections of relative pixel brightness denotes the time at which the image was acquired, and the wiggles represent the relative brightness at the distance along the transect. Dashed lines indicate speed of local ice flow velocity (~245 m a^{-1}; Joughin and others, 2008, 2010). Colored sections (purple, green and blue) highlight examples of advected ogive features that persist from image to image throughout the time-span covered by the Landsat imagery. The lake basin, which persists in a fixed location, is indicated in pink.

attempt to place lake ogives within the broader context of the supraglacial hydrological system.

3.1. Lake-ogive mechanics

The observations presented here suggest that a relationship exists between lake ogives and the more studied wave and band ogives (Nye, 1958; Waddington, 1986; Goodsell and others, 2002). Wave ogives are expressions of surface topography, and band ogives involve the combination of bubble density, grain-size variations, snow cover and debris concentration that alters the surface appearance. The common features leading to the origin of wave and band ogives are: (1) the fixed location of the generating disturbance through which the ice moves (i.e. an icefall), and (2) the seasonally pulsed environmental conditions that imprint on ice moving through the generating disturbance (Nye, 1958; Waddington, 1986). If we consider the ephemeral lake as the fixed generating disturbance, and the presence of water or superimposed ice as the seasonally pulsed condition, then it is apparent that lake ogives are simply a manifestation of wave ogives.

In this description of lake-ogive mechanics, it is essential that the lake remains fixed to act as the generating disturbance, and that the transit time through the lake be at least the duration of a summer season. We showed in Section 2.1 that the position of the lake remains fixed, and we elaborate here on the requirements of the transit time through the lake. However, in defining the transit time through the lake and, generally, considering the mechanism for lake-ogive creation, we must differentiate between the ephemeral lake and the larger topographic basin. An idealization of the lake geometry leading to the lake-ogive morphology is shown in Figure 8. We surmise that the ephemeral lake and the lake ogives are situated in a much larger basin that is equivalent in size to the 'blue' area occupied occasionally by water in Figure 3. In this circumstance, the ephemeral lake (i.e. the generating disturbance) is the much narrower red/yellow region occupied by water every summer in Figure 3. We further speculate that this geometry manifests as a result of large surface depressions created from ice-flow conditions as described by Sergienko and Hulbe (2011). Sergienko and Hulbe (2011) suggest that sticky spots in the bed can lead to substantial ice thickness variations that take surface topographic forms resembling our ogived lakes. The key to these geometries is their asymmetry. The upstream portion is the topographic low and the steepest part of the basin. The rest of the basin opens, primarily, in the downstream direction. If we assume our ogived lakes are similar in geometry, then it is reasonable that the ephemeral lake is always found at the upstream side of the basin. Furthermore, we attribute the 'narrowness' of the ephemeral lake, relative to the larger basin, to the low availability of water volume from melt at these locations. Also from Figure 3, it is clear that the ephemeral lake has a small aspect ratio (length-to-width where width is measured in ice-flow direction). If the ablation regime near one of these lakes were to change and produce enough melt to consistently fill the entire basin with meltwater, then the width of the ephemeral lake would increase, the time for transit through the lake would lengthen and the predisposition of the geometry for ogive formation would be violated. In essence, we would likely not observe ogives at such a location.

The requirement that ice transit time be at least the length of the summer season comes from the discussion of wave ogives by Nye (1958) and Waddington (1986). Those authors investigated ogive patterns and showed how the ogive-generating disturbance is influenced by an annually repeating cycle. The wave-excitation potential found in Waddington (1986) is the convolution of processes that lead to waves on the ice surface, and is determined by width variations, ice speed variations and mass-balance variations. Following Waddington (1986), we can describe the lake-ogive situation as similar to their 'double-step ice-fall model'. The wave excitation potential for the lake-ogive case can be described as an increase in ablation during the time that an ice column is part of the floor of the ephemeral lake, from enhanced lake-bottom ablation (Tedesco and others, 2012), followed by an increase in accumulation from refreezing of the lake water onto the ice column that forms the lake bottom in autumn or early winter. If we neglect the refreezing for now, this wave excitation potential acts over the time it takes to transit the lake, t_{tr}, or the duration of the summer season, t_{s}, whichever is shorter. This can be approximated with

$$t_{\mathrm{tr}} = \frac{W}{U} \tag{1}$$

where W is the width of the ephemeral lake and U is the annual ice velocity. Thus, the maximum wave amplitude, A (i.e. the height of the lake-ogive band), will occur when the time for transit through a lake is equal to, or longer than, the length of time that the ephemeral lake exists (i.e. the length of the summer season):

$$A = \min(t_{\mathrm{tr}}, t_{\mathrm{s}})(\dot{b}_{\mathrm{lake}} - \dot{b}_{\mathrm{s}}) \tag{2}$$

where $\dot{b}_{\mathrm{lake}}$ is the enhanced lake-bottom ablation and $\dot{b}_{\mathrm{s}}$ is the surrounding bare ice ablation.

Equation (2) neglects the superimposed ice component because we have no measure for lake depths or lake bottom bathymetry, which would be necessary to consider refreezing of lake water. Equation (2) describes the situation in summer and contains the important variables. With these two equations, we can address specific points about lake-ogive production. First, very short transit times will not likely produce lake ogives, because the wave amplitude will be too small. Second, lake ogives can still be produced when the transit time is >1 year. However, the additional ogive contribution from superimposed ice may complicate Eqn (2) if transit time is exactly an increment of 1 year. We present a uniform enhanced ablation rate in Eqn (2) and neglect the refreezing, but it may be more accurate to represent the amplitude function as a sinusoid. This sinusoid amplitude will have a negative value for enhanced ablation and a positive value for accreted superimposed ice. If we assume there is symmetry between enhanced ablation rates and freezing rates, as well as symmetry between the length of summer and winter seasons, the ogive band would not exist when transit time is 1 year. This is because the negative/positive wave components would cancel each other out. However, we do not know if the function should be uniform or sinusoidal. Nor do we know whether or not speeds are equal during winter and summer. And finally, we do not know if lake-bottom ablation rates are equal to freezing rates. Thus, we present Eqn (2) as an approximation that is most valid for $t_{\mathrm{tr}} < 1 - t_{\mathrm{s}}$ (years).

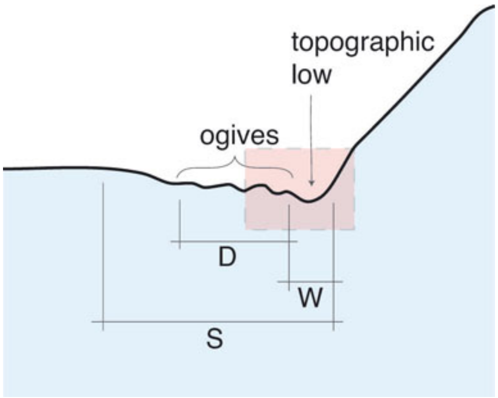

Fig. 8. An idealized schematic of lake ogives and the topographic basin in which they form. Three geometric definitions are given to describe the morphology. S refers to width of the full extent of the lake basin (i.e. the larger topographic basin), W refers to the width of the ephemeral lake, and D refers to the downstream length of the ogive train. The highlighted red box is the section of the geometry that is the focus for the conceptual model in Figure 9.

Using the above equations, we can approximate the size of the lake-ogive wave amplitude, A. We assume the summer season is ~90 days and also assume the effect of enhanced lake-bottom ablation is ~6 cm d^{-1} relative to surrounding ice (Tedesco and others, 2012). The lake-ogive wave amplitude using lake-bottom ablation, $\dot{b}_{\mathrm{lake}}$, of 6 cm d^{-1}, relative to surrounding ablation, $\dot{b}_{\mathrm{s}}$, of 2 cm d^{-1}, should be on the order of 3 m, which seems to be corroborated by the observations presented in Figure 4.

In Figure 9, we schematically illustrate the entire lake-ogive model with a few key ingredients: short (e.g. 60–90 day) melt season; ablation contrast between bare-ice melting and enhanced melting on a lake bottom (Tedesco and others, 2012); wintertime refreezing of standing water; movement of underlying glacial ice through the lake's position; and movement of superimposed ice with the glacial ice flow. The effect of these ingredients is depicted by the

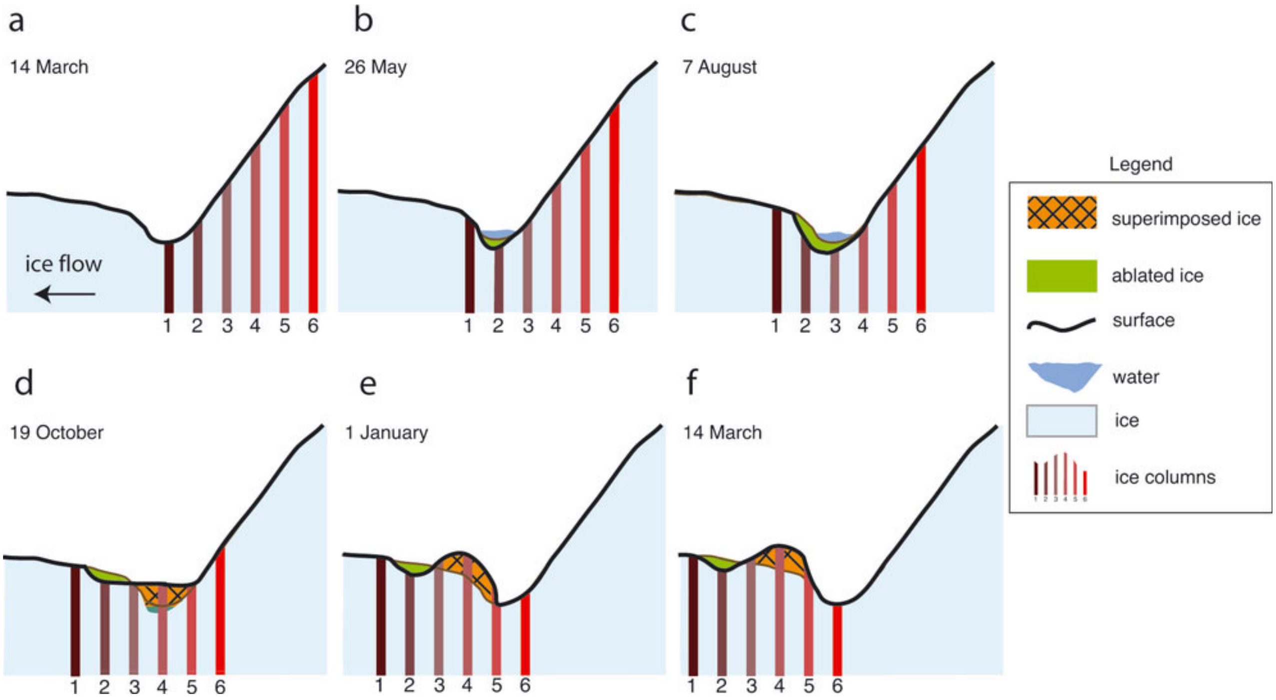

Fig. 9. Conceptual model of lake-ogive origin, with six panels showing the lake ogive evolution over a 1 year period. Six vertical ice columns represent Lagrangian tracers that advect through the bedrock-fixed reference frame. (a) Six ice columns are located upstream of a topographic basin on 14 March. The ice surface is shown in black. This steady-state surface is shown as brown in subsequent panels. (b) The same six ice columns advect through the topographic basin on 26 May. Water has accumulated in the basin, and enhanced lake bottom ablation has created a small deficit below the steady-state ice-sheet surface at ice column 2. (c) Water volume has increased in the basin; the deficit at ice column 2 has advected out of the basin. Enhanced lake bottom ablation has created more deficit at ice column 3. (d) The ice deficit at ice column 2 is completely out of the basin and will advect downstream. The standing water at ice columns 3–5 is mostly refrozen as superimposed ice. The superimposed ice is now an accretion above the steady-state surface. (e) The ice deficit at ice column 2 and the accreted superimposed ice advect away from the topographic basin. (f) One lake ogive wave is now downstream of the topographic basin. Ice from upstream replenishes the topographic basin and prepares it for the next year's lake ogive.

contrast between the three ice columns in Figure 9. In this schematic, one ice column traverses the lake during the melt season, and thus has a portion of its upper layer anomalously ablated relative to the other ice columns. This extra ablation produces a small deficit in surface topography that advects downstream. Also depicted in Figure 9 is an ice column that moves through the lake during the time that the lake's water is being frozen to become superimposed ice which produces a small topographic surplus. This variation between seasonal influences with a continuous supply of newly advected ice from upstream forms repetitive mounds in the surface topography like that shown in Figure 4 which may also display variations in color and albedo, as seen in Figure 5.

Inter-seasonal surface features that are created through supraglacial hydrological processes, such as lake ogives, are formed by the interaction of glacier ice, superimposed ice and water. This interaction is strongly affected by the fact that the surface of the ice sheet is being advected downstream by ice flow. This has been outlined in detail for the lake-ogive morphology above. Current glacier models do not include advection of all three of these phases, and therefore cannot produce lake ogives. Typical flowline models lack hydrology components and advect only the glacier ice, simply disregarding mass that sublimates into air or mass that runs off the ice sheet (as water). More recent 'hydrological-type' glacier models (Clason and others, 2012; Leeson and others, 2012) transport the water phase, but do not include physics for evolution of the glacier ice (from ice dynamics or local ablation). These latter models prescribe a DEM-based surface topography and collect water into local topographic sinks to create supraglacial lakes. However, the supraglacial hydrological system is characterized by a more complex organization than just a collection of supraglacial lakes. We speculate that a model framework that considers the advection of all the water phases may generate the complex behavior of glacier surface hydrology to include interactions between supraglacial lakes, switching on and off of supraglacial channels and the advection of relict features.

We suggest that it is worth being attentive to modeling persistent small-scale surface features such as lake ogives in glacier models. The lake ogive seems to be a natural consequence of the interaction between the various water phases, and is thus an indicator of a properly working glacier model that includes hydrology. Furthermore, the lake-ogive morphology perhaps represents the simplest case study of an advected transient surface feature because we need not consider mass loss via draining. We can, therefore, reasonably neglect mechanical influences that result in fracture, creep closure or variations in basal sliding, and focus on the thermodynamic complexities alone. Surface features that involve these mechanical influences (e.g. moulins or channels) may have broader impacts on the surface hydrological system than lake ogives. Yet any glacier model that contains these more complex surface features must still require the physics necessary for producing lake ogives. Thus, the production of a lake-ogive morphology seems to be a reasonable intermediate model goal. Once this step is completed, additional physics that account for the complexities of moulin or channel generation/evolution can be added.

3.2. Lake-ogive setting

We suggest that lake ogives are a distinguishing morphology associated with the first, highest-elevation lakes to form on the flanks of an ice sheet. However, the sparsity of lake-ogive observations indicates that additional considerations are necessary to more narrowly constrain the lake-ogive setting. This may amount to constraining conditions on the preservation of lake ogives, rather than the creation of lake ogives. Here we elaborate on the conditions responsible for lake ogive presence or absence.

The observations of Lampkin (2011) show that crescent-shaped lakes (i.e. ogive-type) are the highest-elevation lakes. At lower elevations, ogives are not as likely to be generated by lakes due to their greater likelihood of draining subglacially and the overall larger ablation rate that homogenizes the surface appearance. At higher elevations, there is less standing water, reduced runoff and a lower crevasse density. This means that surface lakes at higher elevations will be most likely to export summer meltwater as refrozen lake ice resting on the surface as outlined in the lake-ogive model (Section 3.1).

We suggest that the visual differences in ice types, and the topographic expressions of enhanced lake-bottom ablation and superimposed ice that constitute lake ogives are eventually removed by surface ablation, which increases with decreasing elevation. Furthermore, ogives will be found only downstream of lakes in regions with velocities large enough for transit of ice through the lake location in one annual cycle. Hence, lakes situated at the ELA, where ablation rates are generally small and surface ice velocities are generally large, are prime candidates to form ogives that continue downstream over long distances. At lower elevations, the relatively high surface ablation rates can be expected to erase ogives before the annually repeating sequence forms. We use the SPOT5 visual imagery present in Figures 2 and 5 to measure the downstream length, D, of eight lakes. We also determine ablation rates at these eight lake locations from interpolation of the gridded Ettema and others (2009) model output. We find that the downstream extent of ogives has a negative correlation with ablation rates, $\dot{b}$, as expected (Fig. 10). This means that lakes in regions of high ablation, despite being near the equilibrium line, will potentially erase lake ogives before long ogive trains can be preserved.

We also see that lake-ogive presence is strongly correlated with surface slope. On flatter parts of the ice sheet, the downstream extent of lake ogives is greatest. This is evident in Figure 5 where the ogive locations correspond to nearly flat areas of the ice sheet. A counter-example is also evident in Figure 5 where a fourth surface depression is visible (mid-right of figure) but no lake ogives exist. This depression has a significantly positive slope downstream of its ephemeral lake, unlike the more flattened regions existing downstream of the three nearby lakes. We expect the four lakes to share a local climate, so this highlights the important additional influence of surface slope on the location of ogived lakes. We suggest that the flattened downstream surface does not create the lake ogives but does provide a favorable setting for long ogive trains to be preserved.

Furthermore, it is worth noting that Lake 7 contained 16 visible ogives in Echelmeyer and others (1991) and maintained this general count until 2008 when extreme melting erased most of the lake ogives (Video S1). It seems that long lake-ogive trains are produced when near-constant environmental conditions persist over many seasons. The observed erasure of lake ogives demonstrates the influence of melting as a counter to long-term preservation.

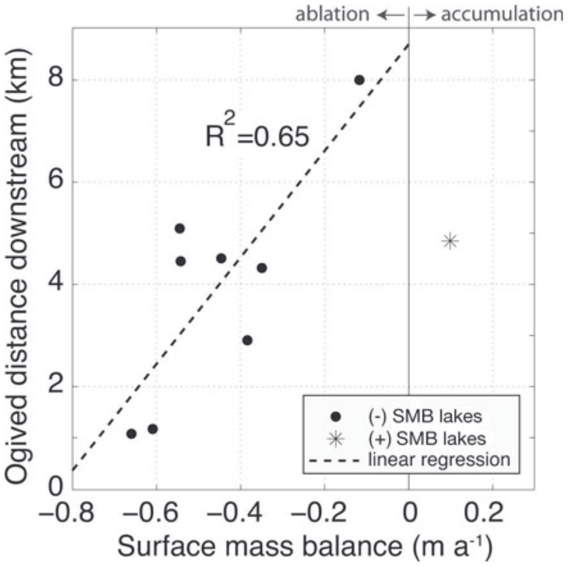

Fig. 10. A selection of eight lakes observable in the SPOT5 visual imagery. The ogived distance downstream, D, is measured from this imagery and plotted against the surface mass-balance (SMB) values, $\dot{b}$, interpolated from the Ettema and others (2009) dataset. A linear regression is performed only for the lakes with a net annual ablation (negative SMB).

We also point towards Figure 2 to demonstrate the potential use of the lake-ogive morphology as an indicator of ice-flow conditions. The lake ogives of Lake 8 seem to have a variable inter-band distance and have a mid-morphology directional change. The idealization of lake ogives relies on a constant annual ice velocity, constant summer ablation rates and a steady ice flow. The true situation may be very different. In fact, we know that other areas of the ablation zone do experience a summertime speed-up (Sundal and others, 2011). This would mean that thinking about the transit time through lakes requires knowledge of the summer velocities, not simply the annual velocities. We ask, what could be gained by a year-long velocity dataset at the location of a lake with ogives? The answer is unknown at this point. The lake ogive bands seem to contain information about past ice-flow conditions, but more extensive study would be required to understand the information contained therein.

While we better understand the setting in which lake ogives exist, a more extensive study, with a field component, would be required to determine the exact setting and sensitivity of lake-ogive morphology. Such a field study could answer some of the remaining questions, such as the exact composition of the alternating bands, the local ice velocity, the evolution of the lake over a season, the ablation rates within the lake, and the role of floating lake ice.

3.3. Related surface features

The lake-ogive morphology can be considered a nascent supraglacial lake in which the lake evolution during each annual cycle is less complex than for lakes further

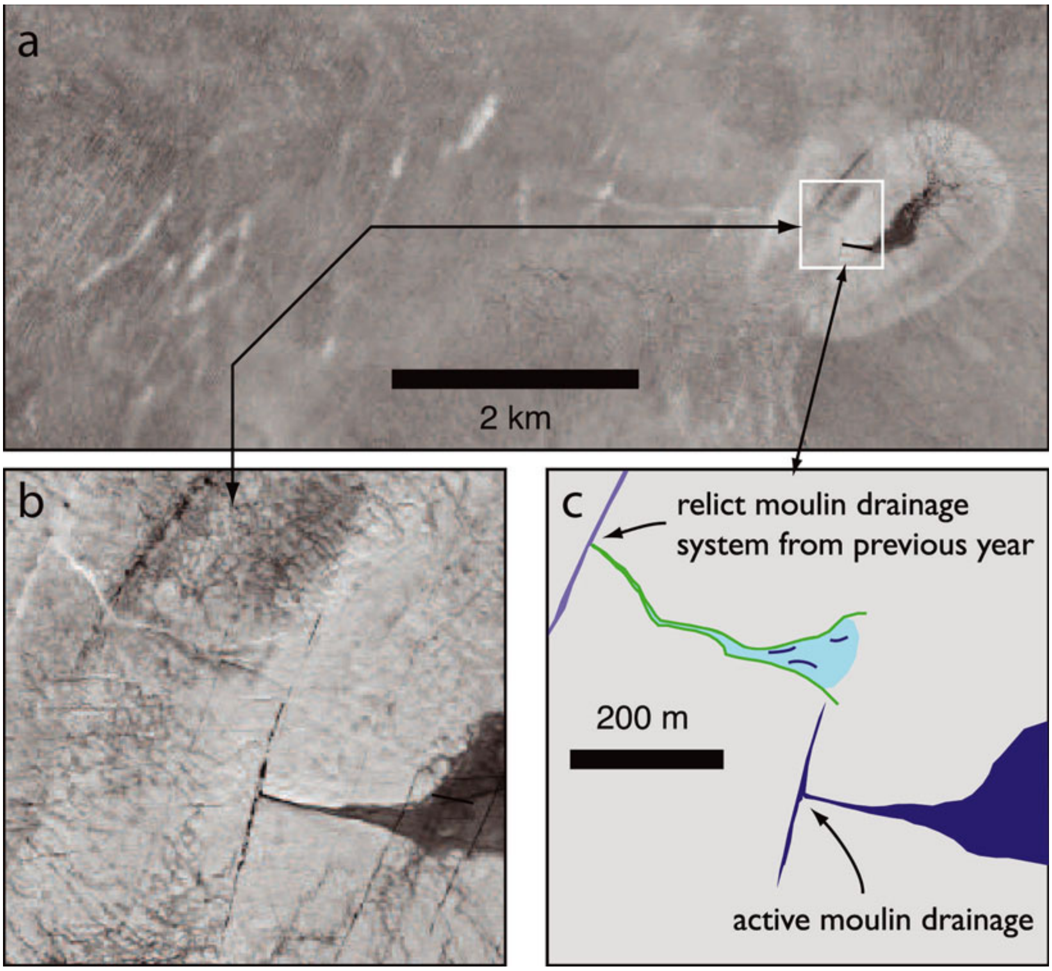

Fig. 11. A recently drained supraglacial lake in Greenland (DigitalGlobe Inc. imagery acquired 6 August 2009). (a) Overview indicating insets where subscenes displayed in (b) and (c) are located. The bright circular structure with standing water in the center is a lake that drained shortly before the image was acquired. (b) Close-up of standing water leading to the moulin that drained the lake. The moulin is located in a crevasse in a large crevasse field with fractures oriented from upper right to lower left (northeast to southwest). At upper left is a relict moulin and watercourse feature that resemble the currently active moulin and watercourse. (c) Interpretive sketch of (b). Imagery provided by the NGA Commercial Imagery Program. Copyright 2009 DigitalGlobe, Inc.

downstream. This lower complexity stems from the necessity to export water from the lake as superimposed lake ice, the absence of moulins, and the limited interaction with other lakes through surface channels. This lower level of complexity is good reason to think about lake ogives. It is also worthwhile to consider the primary dynamic component of lake ogives: ice movement through a bedrock-fixed reference frame. We suggest that, despite differences in setting and geometry, moulins and water-carved channels can also be understood through ice movement in a bedrock-fixed reference frame. Water-carved surface features and moulins are known to persist for several years after their initiation and to be advected through the bedrock-fixed reference frame away from their point of origin. This has been described by Catania and Neumann (2010): ‘both the englacial and supraglacial drainage systems must advect with ice flow... [and]... the englacial and supraglacial system is moved downstream until it can no longer be maintained (i.e. the moulin is cut off from the supra- or subglacial water system possibly by a new crevasse opening upstream of the existing moulin)’.

We show an example of this phenomenon in Figure 11. In the imagery, the supraglacial lake is shown draining into a moulin. The former area of the lake (Fig. 11a) is identifiable by the bright surface appearance surrounding the current lake extent. Displaced downstream relative to the ice flow (west-northwest) by a distance of several hundred meters (i.e. a distance equal to annual surface ice displacement) is a less-bright area of the surface that represents the area of the lake during the previous summer (area just to the left of the box in Fig. 11a). The current drainage pathway is a water-filled channel incised into the lake bottom that leads to a crevasse which initiated the moulin. A relict channel and moulin appear downstream of the lake, which have been advected from their origin at the fixed location of the supraglacial lake. The image does not explicitly show the effect that these relict features have on the local hydrology. Yet we suggest that these relict features will provide pathways for routing surface water and will respond to the thermodynamic/mechanical effects of standing water.

Moulins, water-carved channels and lake ogives contain information about the ice sheet’s recent forcing, but also exert a multi-year influence on local hydrological processes. It remains unclear, however, what contribution these small-scale features make to re-routing surface waters or enhancing ablation. It is very clear that DEM-based models where the topography is static will overlook these secondary hydrological effects, especially when ice flow moves the surface features from their origin. Glacier models which consider the combined interaction of ice flow and thermodynamics, as described in Section 3.2, may resolve the unknown hydrological impacts of these and other small-scale surface features.

4. CONCLUSION

Lake ogives originate as a result of refreezing of lake water, enhanced lake-bottom ablation and modifications of the visual appearance of the ice-sheet surface as it moves through the lake basin under seasonally pulsed environmental conditions. While ground-based observation can likely constrain the lake-ogive mechanism more narrowly, the results presented here are consistent with the ogive wave theory articulated by Waddington (1986) and sources therein. We establish that water accumulates within a geographically fixed basin and eventually refreezes as a series of visible surface bands. This provides a test scenario of complex surface hydrological models in which water is routed and thermodynamically active. The lake ogive is a natural consequence of the hydrological interactions at the ice-sheet surface, and thus could serve as indication that glacier models with hydrology can produce physically meaningful results.

To fully understand ice-sheet surface hydrology, it is important to recognize the spectrum of phenomena that operate on multiple length- and timescales. Our analysis of lake ogives represents one step in this effort because it establishes a hydrological model performance goal that involves lakes at the highest altitude (i.e. those that form near the ELA). Long-term analysis and future predictions of ice-sheet hydrology will require an active parameterization of the advective and thermodynamic facets of this complex system. It will become especially important to incorporate these features into models when climate forcing acts to move the equilibrium line up-glacier or transforms the system to create new lakes, new channels and new moulins.

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REFERENCES

Bamber JL, Layberry RL and Gogineni SP (2001) A new ice thickness and bed data set for the Greenland ice sheet. 1. Measurement, data reduction, and errors. *J. Geophys. Res.*, **106**(D24), 33 773–33 780 (doi: 10.1029/2001JD900054)

Box JE and Ski K (2007) Remote sounding of Greenland supraglacial melt lakes: implications for subglacial hydraulics. *J. Glaciol.*, **53**(181), 257–265 (doi: 10.3189/172756507782202883)

British Glaciological Society (BGS) (1953) Glacier bands: Conference on terminology. *J. Glaciol.*, **2**(13), 229–232

Catania GA and Neumann TA (2010) Persistent englacial drainage features in the Greenland Ice Sheet. *Geophys. Res. Lett.*, **37**(2), L02501 (doi: 10.1029/2009GL041108)

Clason C, Mair DWF, Burgess DO and Nienow PW (2012) Modelling the delivery of supraglacial meltwater to the ice/bed interface: application to southwest Devon Ice Cap, Nunavut, Canada. *J. Glaciol.*, **58**(208), 361–374 (doi: 10.3189/2012JoG11J129)

Echelmeyer K, Clarke TS and Harrison WD (1991) Surficial glaciology of Jakobshavns Isbræ, West Greenland: Part I. Surface morphology. *J. Glaciol.*, **37**(127), 368–382

Ettema J and 6 others (2009) Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modelling. *Geophys. Res. Lett.*, **36**(12), L12501 (doi: 10.1029/2009GL038110)

Goodsell B, Hambrey MJ and Glasser NF (2002) Formation of band ogives and associated structures at Bas Glacier d'Arolla, Valais, Switzerland. *J. Glaciol.*, **48**(161), 287–300 (doi: 10.3189/172756502781831494)

Jezek KC, Drinkwater MR, Crawford JP, Bindschadler R and Kwok R (1993) Analysis of synthetic aperture radar data collected over the southwestern Greenland ice sheet. *J. Glaciol.*, **39**(131), 119–132

Joughin I and 7 others (2008) Continued evolution of Jakobshavn Isbræ following its rapid speedup. *J. Geophys. Res.*, **113**(F4), F04006 (doi: 10.1029/2008JF001023)

Joughin I, Smith BE, Howat IM, Scambos T and Moon T (2010) Greenland flow variability from ice-sheet-wide velocity mapping. *J. Glaciol.*, **56**(197), 415–430 (doi: 10.3189/002214310792447734)

King CAM and Lewis WV (1961) A tentative theory of ogive formation. *J. Glaciol.*, **3**(29), 913–939/912

Krabill WB and Thomas RH (2010) *Pre-IceBridge ATM L2 Icessn elevation, slope, and roughness [970513, 020531, 050514, 060527]*. NASA Distributed Active Archive Center, National Snow and Ice Data Center, Boulder, CO. Digital media: http://nsidc.org/data/BLATM2.html

Lampkin DJ (2011) Supraglacial lake spatial structure in western Greenland during the 2007 ablation season. *J. Geophys. Res.*, **116**(F4), F04001 (doi: 10.1029/2010JF001725)

Layberry RL and Bamber JL (2001) A new ice thickness and bed data set for the Greenland ice sheet. 2. Relationship between dynamics and basal topography. *J. Geophys. Res.*, **106**(D24), 33 781–33 788 (doi: 10.1029/2001JD900053)

Leeson AA, Shepherd A, Palmer S, Sundal A and Fettweis X (2012) Simulating the growth of supraglacial lakes at the western margin of the Greenland ice sheet. *Cryosphere*, **6**(5), 1077–1086 (doi: 10.5194/tc-6-1077-2012)

Motyka RJ, Fahnestock M and Truffer M (2010) Volume change of Jakobshavn Isbræ, West Greenland: 1985–1997–2007. *J. Glaciol.*, **56**(198), 635–646 (doi: 10.3189/002214310793146304)

Nye JF (1958) A theory of wave formation in glaciers (Cambridge Austerdalsbræ Expedition). *IASH Publ.* 47 (Symposium at Chamonix 1958 – *Physics of the Movement of the Ice*), 139–154

Posamentier HW (1978) Thoughts on ogive formation. *J. Glaciol.*, **20**(82), 218–220

Selmes N, Murray T and James TD (2011) Fast draining lakes on the Greenland Ice Sheet. *Geophys. Res. Lett.*, **38**(15), L15501 (doi: 10.1029/2011GL047872)

Sergienko OV and Hulbe CL (2011) 'Sticky spots' and subglacial lakes under ice streams of the Siple Coast, Antarctica. *Ann. Glaciol.*, **52**(58), 18–22 (doi: 10.3189/172756411797252176)

Sundal AV, Shepherd A, Nienow P, Hanna E, Palmer S and Huybrechts P (2009) Evolution of supra-glacial lakes across the Greenland Ice Sheet. *Remote Sens. Environ.*, **113**(10), 2164–2171 (doi: 10.1016/j.rse.2009.05.018)

Sundal AV, Shepherd A, Nienow P, Hanna E, Palmer S and Huybrechts P (2011) Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage. *Nature*, **469**(7331), 521–524 (doi: 10.1038/nature09740)

Tedesco M and 7 others (2012) Measurement and modeling of ablation of the bottom of supraglacial lakes in western Greenland. *Geophys. Res. Lett.*, **39**(2), L02502 (doi: 10.1029/2011GL049882)

Van de Wal RSW, Greuell W, Van den Broeke MR, Reijmer CH and Oerlemans J (2005) Surface mass-balance observations and automatic weather station data along a transect near Kangerlussuaq, West Greenland. *Ann. Glaciol.*, **42**, 311–316 (doi: 10.3189/172756405781812529)

Waddington ED (1986) Wave ogives. *J. Glaciol.*, **32**(112), 325–334

Zwally HJ and Giovinetto MB (2001) Balance mass flux and ice velocity across the equilibrium line in drainage systems of Greenland. *J. Geophys. Res.*, **106**(D24), 33 717–33 728 (doi: 10.1029/2001JD900120)

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