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Automated mapping of near bed radio-echo layer disruptions in the Greenland Ice Sheet

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ABSTRACT

One of the key processes for modulating ice flow is the interaction between the ice and the bed, but direct observations of the subglacial environment are sparse and difficult to obtain. In this study we use information from an extensive radio-echo sounding dataset to identify areas of the Greenland Ice Sheet where internal layers have been influenced by near-bed processes. Based on an automatic algorithm for calculating the slope of the internal radio-echo layers, we identify areas with disrupted layer stratigraphy. We find that large parts of the northern portion of the ice sheet are influenced by locally confined mechanisms that produce up-warping or folds in the layer stratigraphy inconsistent with the surface and bed topography. This is particularly evident at the onset of ice streams, although less dynamic areas close to the ice divide also contain imprints of layer disturbances. Our results show that the disturbances are found in many different flow and thermal regimes, and underscore the need to understand the mechanisms responsible for creating them.

1. Introduction

During the past several decades, the Greenland Ice Sheet (GrIS) has been extensively surveyed by ice-penetrating radar (also referred to as radio-echo sounding: RES) (e.g., Gudmandsen, 1975; Gogineni et al., 2001). This has enabled improved ice-volume estimates through the years (e.g., Bamber et al., 2001, 2013a), and detailed maps of regional and local bed topography (e.g., Bamber et al., 2013b; Gogineni et al., 2014). In addition to measurements of ice thickness, the echograms often also reveal internal reflecting horizons in the ice. These features, here referred to as internal layers, represent a powerful source of information on ice-sheet history and dynamics. The internal layers are the dielectric signature of changes in density, impurity content, acidity and/or crystal orientation (e.g., Millar, 1981; Fujita et al., 1999; Eisen et al., 2007). Several studies have demonstrated that the stratigraphy of internal layers can be used to reconstruct past ice flow, surface mass balance and basal melt rates if the layers are assumed to be isochrones, i.e., of the same age (e.g., Fahnestock et al., 2001; Conway et al., 2002; Ng and Conway, 2004; Siegert et al., 2005; Buchardt and Dahl-Jensen, 2007; Leysinger Vieli et al., 2011). Further, theoretical studies (Parrenin et al., 2006) have demonstrated that the layer slopes also contain information on ice flow, and Ng and King (2011) constructed a mathematical framework to investigate how slope information propagates in near-surface radar data.

Recently, an extensive study by MacGregor et al. (2015) presented a dataset of traced layers covering most of the echograms available from the GrIS, and linked the traced internal layers to ice-core sites, where the age of the ice is known. Thus age-horizons have been constructed for most of the ice sheet, providing an important tool for constraining the past dynamics of the GrIS. The combined tracing of internal layers and construction of radiostratigraphy is a laborious and time-consuming task. Therefore, alternative approaches to avoid directly tracing the layers have been developed in several previous studies. This includes the development of semi-automatic methods for picking layers in near-surface RES data (Onana et al., 2015), for automatically identifying subsurface signals in RES data from Mars radar sounders (Ferro and Bruzzone, 2012, 2013; Freeman et al., 2010), and for tracing a distinct pattern of internal layers by fitting a shape function (Karlsson et al., 2013). Yet again, other studies have tried to circumvent the layer tracing problem by instead quantifying the continuity of the layers (Karlsson et al., 2012) or calculating the slope of the layers (Sime et al., 2011; Panton, 2014).

Finally, RES data have also been used to directly or indirectly extract information about the basal conditions of ice sheets (Fahnestock et al., 2001; Carter et al., 2007; Buchardt and Dahl-Jensen, 2007; Oswald and Gogineni, 2012). This is aided by the recent improvements to RES equipment and processing (Rodriguez-Morales et al., 2014), making it possible to sound the

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deepest internal structure of the GrIS with great clarity. Some radio-echograms show substantial disturbances to the internal layers (often in the form of up-welling and/or folding), and in some cases the disturbances take up more than half of the ice sheet column, with a horizontal extent on the order of ten kilometers. Bell et al. (2014) proposed that these features are correlated with the occurrence of refrozen meltwater. In contrast, the stratigraphically warped bottom section of the NEEM ice core was explained by folding due to the differences in rheological properties of the Eemian and glacial ice (Dahl-Jensen et al., 2013). And most recently, Wolovick et al. (2014) suggested that the features could be formed by non-uniform and time-variable basal sliding.

In short, internal layers of ice sheets have been observed to be influenced by processes acting near the bed, resulting in a stratigraphy that cannot be explained by surface or bed topography alone. MacGregor et al. (2015) used the term 'disrupted radiostratigraphy' to describe the RES observations of disturbances in the internal layer stratigraphy apparently induced near the bed. We extend on this term and use 'unit of disrupted radiostratigraphy', or *UDR*, in order to avoid implying a specific formation process and to indicate that the disruptions have a finite physical extent.

Like MacGregor et al. (2015), we utilize information from the internal layers in the GrIS to map the signature of UDRs. In contrast to methods where the basal conditions are observed by the quantitative properties of the echogram, e.g., where the presence of liquid water is detected using the strength and specularity of the RES signal (Carter et al., 2007; Oswald and Gogineni, 2012; Schroeder et al., 2013, 2015), we instead study the problem based on interpretation of internal layer slopes.

Our analysis is based on an automated method for extracting information on the internal layer slopes (Panton, 2014), and on a simple mathematical framework demonstrating how changes in the basal environment can leave an imprint on the internal layers.

2. Radio-echo sounding data

We rely on a publicly available dataset acquired over the years 1999–2014 by the Center for Remote Sensing of Ice Sheets (CReSIS; University of Kansas). The data acquisition campaigns have covered almost all of the GrIS allowing for the construction of, for example, detailed maps of bed topography (Bamber et al., 2013a) and internal layer depths (MacGregor et al., 2015; Karlsson et al., 2013). In the dataset we are using, the bedrock and surface have already been picked by CReSIS.

The data for this study were acquired using two different and continuously developed radar systems. The radar system operating from 1999 to 2009 had a centre frequency of 150 MHz, and a bandwidth of 17 MHz with a peak transmit power of 200 W. From 2010 onwards, the centre frequency was changed to 195 MHz with a bandwidth of 30 MHz and with increasing peak transmit power up to 1200 W. More information on the radar systems is provided by Gogineni et al. (2001) and Rodriguez-Morales et al. (2014).

3. Methods

Our automatic detection of UDRs is based on the observation that the disturbances exhibit increasing layer slopes with depth. To further develop this hypothesis, we discuss the evolution of sloping internal layers using a simple theoretical framework in the section below. Then we briefly present the automatic layer slope algorithm first published in Panton (2014) and finally we show how the layer slope field can be used to detect the signature of UDRs. Our methods described below are comparable to what was developed by MacGregor et al. (2015) and the differences between these will be discussed later.

3.1. Theoretical framework

The depth of an internal layer is determined by the ice thickness, surface accumulation, basal melting, spatial gradients in ice flow velocity, and ice sheet evolution. The conditions at the bed may affect the internal layers through variations in basal melt rate and changes in ice flow mode. In this context the basal melt rate influences the vertical velocity by dragging the layers downwards in the ice column for increasing melt rates (e.g., Fahnestock et al., 2001; Buchardt and Dahl-Jensen, 2007). Changes in ice flow mode are exemplified by the "Weertman effect" (Weertman, 1976) where the internal layers move downwards when there is a change from no sliding to sliding, or upwards when the change is from sliding to no sliding. The latter case has also been referred to as "sticky spots" (Alley, 1993), and has been in observed numerous places particularly in West Antarctica (e.g., Anandakrishnan and Alley, 1994; Joughin et al., 2006).

We calculate the depth of an internal layer by considering the motion of particles in a two-dimensional velocity field $\{u(x,z,t), w(x,z,t)\}$, where x is the horizontal coordinate, z is the vertical coordinate and t is time. We define the direction of horizontal ice flow to be along the x-axis. A line connecting two particles P_1 and P_2 will form an angle α with the horizontal, defined by $\tan\alpha = \frac{\mathrm{d}z}{\mathrm{d}x}$, where $\mathrm{d}x = x_{P_2} - x_{P_1}$ is the horizontal distance between the particles and $\mathrm{d}z = z_{P_2} - z_{P_1}$ is the vertical distance (cf. Fig. 1A, inset). If the particles are of the same age, the line connecting them will by definition be an isochrone. Generally, two particles will remain at the same vertical distance dz relative to each other if they experience the same vertical velocity w. Thus, if the vertical velocity field is constant in time and does not change horizontally, dz will always be zero, if the particles start at the same z-position, and the angle α will remain zero regardless of spatial changes in the horizontal velocity. In other words, there must be a horizontal gradient in the vertical velocity in order to induce a slope in the isochrones.

A horizontal gradient in the vertical velocity may occur due to different processes. The full expression for the vertical velocity includes surface accumulation rate, basal melt rate, horizontal velocity, horizontal gradients in surface elevation, horizontal gradients in bed elevation, and so-called velocity shape functions that describe how the velocities vary with depth (cf. Waddington et al., 2007). All of these processes may induce a horizontal gradient in the vertical velocity, however, over the spatial scale of a typical radio-echogram (10^1–10^2 km) some of the processes can be neglected. For example, in the interior of GrIS the surface accumulation rate varies smoothly over distances typically $\geq 10^2$ km (e.g., Burgess et al., 2010), and thus have a small horizontal gradient over the extent of a typical radio-echogram. The same is true for the surface slope and the horizontal velocity. Our method of detecting increasing layer slopes with depth will therefore primarily map areas with changes in basal melt rates, velocity shape function, and bed topography.

We will begin by discussing the impact of changing basal melt rates. Assume a constant and uniform accumulation rate and ice thickness, and small horizontal changes in u (i.e. $\partial u/\partial x \ll \partial w/\partial z$). At the surface the vertical velocities will be the same everywhere because w at the surface is controlled by the accumulation rate. At the bed the vertical velocity is controlled by the basal melt rate, thus if the basal melt rate varies horizontally along the direction of flow, the change in w with depth will differ along flow. This introduces a horizontal gradient in w and this gradient will increase with depth as the vertical velocity approaches the local basal melt rate. Thus, the difference in vertical velocity between two points will increase with depth, leading to an increase in dz and a corresponding increase in layer slope α with depth. This is illustrated in Fig. 1.