U.S. Geological Survey Benchmark Glacier Project:
Firn Density and Stratigraphy Observations from USGS Benchmark Glaciers
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Overview: This document describes firn core data collected as a part of the U.S. Geological Survey Benchmark Glacier Project.

SUMMARY

The topmost layers of accumulation zones on mountain glaciers and ice sheets comprise porous snow and firn. The structure and material density of firn impacts meltwater retention, meltwater runoff, and surface-elevation changes. Presently, the dataset includes firn-core observations from Site EC (UTM zone 6N, E394619, N6700393) on Wolverine Glacier on the Kenai Peninsula in Alaska. EC is in the glacier's accumulation area at an elevation of 1350 m.

PURPOSE

This dataset comprises measurements of firn density, ice-lens stratigraphy, and annual layers from USGS Benchmark Glaciers. Herein we describe the measurements and outline the techniques used to gather and process the data.

METHODS

Firn coring at site EC began during the spring glacier mass balance field campaign in 2016. Since then, cores have been drilled during each spring (typically late April/early May, coinciding with the end of the accumulation season) and each fall (typically late August/early September, coinciding with the end of ablation season). In addition to the spring and fall cores, cores were also drilled in June, July, and August in 2016, and June and July in 2017.

Note that the spring and fall measurements were conducted close to but not exactly at the end of the accumulation and ablation seasons, respectively. As such, point mass balances derived from these data are site balances on the date of core acquisition and not winter, summer, or annual point balances.

Field techniques:

Measurements start from the surface, and as such include both snow and firn. The dataset does not explicitly classify the material as snow or firn, this can be inferred from the annual layers. During spring field campaigns, near-surface density is measured by digging a snow pit of approximately 1 m depth. Density is measured on the pit wall using a snow-density wedge sampler. Cores are drilled from the bottom of this snow pit. In fall campaigns, cores are drilled from the surface.

Cores are drilled using a FELICS corer (Ginot and others, 2002). Typically, we aim to reach a depth of at least 25 meters below the surface. Each core drive recovers a section of core. We measure the length and mass of each section. Long sections are split into shorter pieces, aiming for lengths of approximately 25 to 30 cm. The core sections have a diameter of 5.7 cm. We measure diameter on random core sections to ensure that this diameter is consistently standard.

Cores are inspected visually for ice lenses and dark layers. Ice lenses are recorded either as the total thickness of all ice lenses within the core, or the discrete depth and thickness of individual ice lenses within the core. Not every ice lens observed was recorded, so these data reflect a minimum. For some cores ice lenses were not recorded.

Dark, dirty, and/or dusty layers are interpreted as end-of-melt-season surfaces from previous years. We corroborate this end-of-melt season surface against glacier mass balance measurements, which provide independent validation of this stratigraphy.

The bottom depth of each coring drive is measured and recorded as the Sample Bottom Depth (SBD). All data are entered by hand into a field notebook. Additional observations (e.g., if the core break was uneven) for each core section are also included in the field notes.

Processing:
Field notebooks are digitally scanned, and the data are then manually entered into a spreadsheet. Core section (sample) density is calculated by dividing the core section mass by its volume. We then calculate the depths of layer boundaries ("layer_top" and "layer_bottom"). Layer boundaries can differ slightly from the depths of the core section boundaries due to small uncertainties in measuring the SBD and core lengths. Calculating these layer boundaries corrects for any discrepancies between the SBD and the cumulative measured core lengths. The resulting continuous depth-density profile is necessary to compute cumulative_SWE and cumulative_density. The sample density is not explicitly included in the data release but can be calculated with the 'mass' and 'volume' columns.

When ice lenses are present, we also calculate the density of the porous firn in a layer neglecting the mass of ice lenses. To do so, we subtract the mass of the ice lenses (assuming an ice density of 900 kg m^{-3}) from the layer mass and subtract the volume of the ice lens from the layer volume to isolate the porous firn mass and volume that is independent of solid ice lenses.

DATA
The data are distributed as .csv files with filename [GLACIER]_[SITE]_firn_[DATE].csv, with [GLACIER] and [SITE] being the glacier and site at which the measurements were taken, respectively, and [DATE] being the date that the core was drilled (date format YYYY.MM.DD). Each .csv file is data for one core. The data are organized in columnar form. Below we briefly describe each column. Mass is reported in m water equivalent (m w.e.) (Cogley and others, 2011). Uncertainty estimates are provided where it is possible to estimate the overall magnitude of measurement error, but uncertainty quantification is not comprehensive or well-constrained. Missing data or no data are left blank.

annual_layer_depth: depth of annual layer (cm). This is the depth below the surface of any dark, dirty, and/or dusty annual layers observed in the core. Annual layer depth uncertainty is estimated as +/-1 cm.

annual_layer_year: year of the annual layer (year). This is the year corresponding to any dark, dirty, and/or dusty annual layers observed in the core. These layers are interpreted as the surface at the end of the melt season in that year that have since been buried. The year of the annual layer is certain unless noted otherwise in the comments.

Comments: Any germane comments about the core section, e.g. core sections where the coring dogs hit ice or damaged the core section. If ice lenses were observed and are noted in the Comments, but ice_layer_height_all is empty, then ice lens is located within the core section, but its specific location was not recorded.

cumulative_density: cumulative density (g cm^{-3}). This is the cumulative or 'bulk' density of the firn from the surface to layer_bottom.

cumulative_SWE: cumulative snow water equivalent (m w.e.). This is the cumulative mass of the firn from the surface to layer_bottom.

density_no_ice: density of firn-only (g cm^{-3}). Density of only the porous firn material of the layer i.e., layer_density with the ice lens portion removed (if ice lenses were present). We assume an ice density of 0.9 g cm^{-3}.

diameter: diameter of the core section (cm). The FELICS corer recovers cores with a very consistent 5.7 cm diameter. Core diameter uncertainty is estimated as +/- 0.1 cm.

grain_size: average grain size (mm). Presently we do not measure this but include it as a placeholder for potential future measurements.

ice_lens_height_all: ice lens location (cm). For each ice lens observed in the core section, this is the height of the bottom of the ice lens above the SBD. If multiple ice lenses were recorded, this is a comma-separated list. If ice was observed and noted in the Comments or ice_lens_thick_all, but ice_layer_height_all is empty, then the ice lens is located within the core section, but its specific location was not recorded.

ice_lens_height_sum: ice lens bottom (cm). If multiple ice lenses were observed, this is the height of the lowest (closest to the layer bottom) lens. Height here is the distance between the SBD and the bottom of the ice lens. If a single ice lens was observed, or if the ice lens thicknesses were summed in the field notes, this is the same as ice_layer_height_all.

ice_lens_thick_all: ice lens thickness (cm). For each ice lens observed in the core section, this is the thickness of the ice lens. If multiple ice lenses were recorded, this is a comma-separated list.

ice_lens_thick_sum: cumulative ice lens thickness (cm). The summed thickness of all ice lenses in the sample. If a single ice lens was observed, or if the ice lens thicknesses were summed in the field notes, this is the same as ice_layer_thick_all.

measurement_type: type of measurement (unitless). P is a pit measurement (e.g., density from a wedge cutter on a snow pit wall). C is a core measurement (e.g., density of core sections).

layer_bottom: bottom of the layer below the surface (cm). This is calculated for the i^{th} row by: $layer\_bottom_i = (SBD_i + SBD_{i+1} - length_{i+1})/2$, or the average of the SBD and the next drive's SBD minus the core section length.

layer_density: density of the layer (g cm^{-3}). This is the same as the density of the core section.

layer_top: top of the layer below the surface (cm). This is the same as the 'layer_bottom' from the previous row in the data, except at the surface where layer_top is 0.

layer_SWE: layer snow water equivalent (m w.e.). This is the mass of the layer, determined by using the sample density and the computed layer thickness.

length: length of the core section (cm). Length is 10 cm for the wedge sampler (width of the sampler). Length uncertainty is estimated as +/-1 cm. This uncertainty stems mostly from core breaks that are not exactly perpendicular to the core axis.

LWC: Liquid water content (%). Presently we do not measure this but include it as a placeholder for potential future measurements.

mass: mass of the sample (g). The sample can be either a core section or a wedge cutter sample. Mass uncertainty is estimated as +/-5 g, based on the resolution of the spring scale. Some mass measurements could be biased high because of drill shavings that can stick to the outside of the core, but this is expected to be small.

SBD: Sample Bottom Depth (cm). This is the depth of the bottom of the borehole after each coring drive, measured with a tape measure to the nearest cm. For coring drives that yield multiple core sections, the SBD is calculated by subtracting the core section lengths from the measured SBD.

volume: volume of the sample (cm^3). The sample is either a wedge cutter sample or a core section. Core section volume is calculated as the volume of a cylinder $\pi r^2 h$, where r is the core radius and h is the core section length. Some core sections have very uneven core breaks or portions of core missing (e.g., where the core dogs chewed into the core). We have made our best effort to note these sections in the Comments field. These core sections have larger volume and density uncertainties. In general, the volume of material missing can be estimated to be less than 10% of the total volume of the core section. Note that any estimates of missing volume are not included in our calculated densities.

temperature: Temperature (°C). Presently we do not measure this but include it as a placeholder for potential future measurements.

SUGGESTED CITATION

Stevens, C.M., Sass, L.C., Florentine, C.E., Mcneil, C.J., Baker, E.H., Bollen, K.E., 2023, Firn density and stratigraphy observations from USGS Benchmark Glaciers: U.S. Geological Survey data release, https://doi.org/10.5066/F7610XHQ

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