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Supporting Information for

The abandoned ice-sheet base at Camp Century, Greenland, in a warming climate

William Colgan[1,2], Horst Machguth[3,4], Mike MacFerrin[2], Jeff D. Colgan[5], Dirk van As[6] and Joseph A. MacGregor[7]

[1]Lassonde School of Engineering, York University, Canada
[2]Cooperative Institute for Research in Environmental Sciences, University of Colorado, United States
[3]Department of Geography, University of Zurich, Switzerland
[4]Department of Geosciences, University of Fribourg, Switzerland
[5]Watson Institute, Brown University, United States
[6]Department of Glaciology and Climate, Geological Survey of Denmark and Greenland, Denmark
[7]Cryospheric Sciences Laboratory (Code 615), NASA Goddard Space Flight Center, United States

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Introduction

This supporting information document provides an expanded written description of the methodology used. This document contains four supporting text sub-sections (S1 to S4) and six supporting figures (S1 to S6). This supporting information does not introduce any new data sets that have not been previously published. Consistent with AGU data policy, a statement is included in the acknowledgements section identifying how the previously published data sets we employ can be accessed.

S.1. Nature and Quantity of Abandoned Wastes

The abandoned infrastructure buried at Camp Century represents considerable physical waste. USACE reports indicate approximately 2300 t of material were transported to Camp Century by over-snow traverse in both 1959 and 1960 [*Clark*, 1965]. While less well-documented, materially-intensive projects were undertaken at Camp Century through at least 1962, such as building the 500-m-long under-snow railway with an operating locomotive [*Abele*, 1964]. Assuming the documented 1959–1960 material transport to Camp Century is also reflective of the less well documented 1961–1962 period, the physical waste presently residing at the depth of the Camp Century tunnels is approximately 9200 t.

The main types of chemical waste now residing at Camp Century are likely petrochemicals and polychlorinated biphenyls (PCBs). Despite being powered by a portable nuclear generator, Camp Century still consumed approximately 6600 L d^{-1} of diesel fuel, primarily to refuel over-snow tractors [*Lufkin and Tobiasson*, 1969]. Assuming conservatively that a one month reserve was present at Camp Century when abandoned, the diesel fuel now residing at Camp Century is approximately $2.0 \cdot 10^5$ L. This may likely be a lower bound, however, as Camp Century was exclusively powered by diesel generators during its last four years of seasonal occupancy. PCB contamination often represents a substantial remediation burden at former Distant Early Warning (DEW) System military bases, which were built along the Arctic Circle in the 1960s [*Poland et al*., 2001]. While we cannot simply estimate the quantity of PCBs now residing at Camp Century, given the above historical context, the null hypothesis must be that PCBs are present there. Further, they likely constitute a non-trivial quantity of chemical waste, and are indeed likely the most consequential pollutant at Camp Century, given the ease with which they disperse and bio-accumulate in the Arctic ecosystem, as well as their longevity and toxicity at low concentrations [*Grannas et al*., 2013; *Pavlova et al*., 2015].

Liquid biological and radiological wastes were interred in unlined sumps beneath the depth of the Camp Century tunnels. Grey water production, including sewage, at Camp Century was 190 L per person per day [*Lufkin and Tobiasson*, 1969]. Assuming a minimum of 85 occupants and four years of year-round operation, there is likely approximately $2.4 \cdot 10^7$ L of grey water buried at Camp Century. This is a lower limit, as occupancy increased to 200 persons during the summer and the period of year-round occupancy was followed by three years of seasonal occupancy. The USACE record the disposal of $4.2 \cdot 10^8$ Bq of low-level radioactive coolant waste into a firn sump during the 1962 calendar year [*Clark*, 1965]. Assuming this rate of coolant disposal is characteristic of the portable nuclear generator's 33 months of continuous operation, between October 1960 and July 1963, the total low-level radioactive waste would have been $1.2 \cdot 10^9$ Bq at the time of disposal. This excludes any potential non-coolant radiological waste.

S.2. Extent and Depth of Abandoned Wastes

We assessed the present distribution of abandoned wastes by georeferencing an "as built" Camp Century site map using 1977–1986 surveying of the borehole location and advection associated with ice flow [*Kovacs*, 1970; *Gundestrup et al*., 1987]. We estimate the positional accuracy of the 2020 georeferenced site map to be ±20 m (Figure 2). The "as built" site map from *Kovacs* [1970] differs from the oft-cited map of *Clark* [1965] in several ways, most importantly by including the experimental railway track and the extended tunnel leading to the unlined disposal sump for radiological waste. The Camp Century tunnel network extends over an area of 1.1 × 0.5 km, oriented approximately SW-NE. While comprehensive, the "as built" site map does not include waste trenches that were used "in the same manner as in normal sanitary fills" [*Clark*, 1965]. An unspecified number of unlined waste trenches likely reside northwest of Camp Century, although their position and extent are poorly documented.

We infer the vertical ice advection profile at Camp Century from in situ observations of firn density and accumulation rate (Section S.3). We use this site-specific inferred vertical advection rate profile to estimate the post-1960 depth of solid and liquid wastes at Camp Century. Buried solid waste at Camp Century spans an appreciable depth range. Trenches were initially cut-and-covered approximately 8 m below 1960 surface [*Abele*, 1964]. While the largest infrastructure, such as buildings and the railway, were located at the trench bed, we acknowledge that appreciable smaller infrastructure, such as vehicles and outbuildings, were located at the 1960 surface. From inferred vertical ice advection rates we estimate that solid waste at 8 m depth in 1960 (equivalent ice age of 10 a) was advected to approximately 36 m depth in 2015 (equivalent ice age of 65 a), and will be advected to approximately 67 m depth in 2090 (equivalent ice age of 140 a).

Due to the efficient movement of liquids within permeable firn, the burial depth of liquid wastes at Camp Century is less certain. The geometries of the Camp Century disposal sumps have not yet been surveyed. Comparable unlined disposal sumps at other ice-sheet sites, broadly analogous to those used for grey water and reactor coolant disposal at Camp Century, have been observed to melt to approximately 35 m below the trench bed, which would be approximately 43 m below 1960 surface, before spreading laterally and forming domed voids with appreciable air space [*Clark*, 1965; *Ostrom et al*., 1962]. It is unclear whether diesel fuel, which has a lower freezing temperature than the mean annual air temperature at Camp Century, remains a homogenous liquid or has chemically disassociated and refrozen in the past 55 years. In either case, the rigid diesel fuel storage tanks have likely ruptured since 1969, due to the pressure of overburden firn. From inferred vertical ice advection rates we estimate that liquid waste at 43 m depth in 1960 (equivalent ice age of 80 a) was advected to approximately 65 m depth in 2015 (equivalent ice age of 135 a), and will be advected to approximately 93 m depth in 2090 (equivalent ice age of 210 a).

Ice-penetrating radar provides independent insight on the depth distribution of the abandoned wastes at Camp Century. Buried solid wastes are expected to manifest as strong, anomalous radar reflections that are distorted relative to adjacent near-surface strata. This character is due to both the effect these wastes upon the local stratigraphy and their large dielectric contrast with the surrounding firn. Refrozen water masses, possibly associated with liquid waste sumps, may also be discernible from the surrounding firn at specific radar frequencies [*Catania and Neumann*, 2010]. Since 1993, NASA has conducted numerous airborne campaigns to assess ice-sheet mass balance, with many flights including VHF (140–210 MHz) radar depth sounders to measure ice thickness [*Gogineni*, 2012]. Anomalous fade-outs in received radar energy are often visible in those data when passing over Camp Century, suggesting the presence of buried solid wastes. Unfortunately, the multi-meter vertical resolution of the VHF radar profiles is insufficient to unambiguously resolve the depth of abandoned wastes. Data quality is further limited by the higher aircraft altitude, and thus higher speed, of most of the Camp Century fly-overs, where the aircraft is often transiting between Thule AB and targets of interest elsewhere in Greenland.

Since 2010, many NASA flights have also included UHF (565–885 MHz) “accumulation” radar to measure near-surface (< 500 m) ice stratigraphy at sub-meter resolution [*Leuschen*, 2014]. While the majority of these flights are slightly north of the present Camp Century site, a limited number of E-W transects intersect the present location of abandoned wastes (Figure S5). These transects detect anomalous non-conformable reflectors at the inferred trench location at 35±5 m depth (Figure 3), consistent with that predicted from our 1-D modeling. The horizontal and vertical resolution of even the UHF radar profiles is insufficient to confidently delineate tunnels and sumps. The limited spatial extents of tunnels (approximately 6 m) and refrozen sumps (approximately 35 m) also makes it difficult to independently assess their geometry from airborne radar data with an along-track sampling frequency of approximately 20 m. The UHF radar, however, does resolve local warping of near-surface layers beneath Camp Century, presumably due to the deformational closure of void spaces associated with tunnels and sumps. While we have identified multiple radar reflections from depth consistent with solid wastes, we have been unable to identify any radar reflections from depths consistent with refrozen sumps. This is most likely due to the lack of UHR radar flightlines coincident with refrozen sumps, rather than an inability of the radar systems to penetrate to detect such features.

S.3. Vertical Advection

We infer the vertical ice advection profile at Camp Century from the observed firn density profile, measured to 100 m depth by bulk sampling in an inclined tunnel (Figure S3-A), and 50-year mean accumulation rate [*Kovacs et al., 1969*; *Buchardt et al*., 2012]. We first we numerically integrate firn density (*ρ*) with depth (*z*) to yield cumulative water equivalent accumulation with depth (*c*; Figure S3-B).

$$c_i = \sum_{z=0}^{z=i} \rho_i \cdot \Delta z \qquad \text{Eq. S1}$$

where depth increases from 0 at the ice sheet surface to z_i at a given depth (*i* represents vertical index). We perform calculations with a vertical increment (*Δz*) of 1 m. Invoking the assumption of steady-state accumulation rate, we then divide the cumulative accumulation with depth profile by long-term water equivalent accumulation rate ($\bar{c}$ = 0.32 mWE a^{-1}) to yield firn age with depth (*t*; Figure S3-C):

$$t_i = \frac{c_i}{\bar{c}}. \qquad \text{Eq. S2}$$

We then perform a node-centered finite difference of firn depth (*z*) relative to firn age (*t*) to yield vertical advection rate with depth (*w*; Figure S4-D):

$$w_i = \frac{(z_{i+1} - z_{i-1})}{(t_{i+1} - t_{i-1})}. \qquad \text{Eq. S3}$$

For sign convention we take *z* and *w* as positive downward from the ice sheet surface.

These inferred profiles, specific to the Camp Century site, permit us to estimate both the steady-state vertical advection velocity at a given depth and the downward vertical displacement from a given depth over a given period. To demonstrate that this vertical advection profile is reasonable, we also compute the associated firn compaction rate profile (*f*) by subtracting advection rate from steady-state accumulation rate ($\bar{c}$; Figure S4):

$$f_i = \bar{c} - w_i \qquad \text{Eq. S4}$$

The inferred firn compaction rate decreases to < 0.05 m a^{-1} at the 65 m firn-ice transition depth, where first-principles suggests it should reach zero. Cumulative firn compaction reaches 0.46 m a^{-1} at this depth. This inferred total firn compaction suggests that 0.89 m a^{-1} of surface snowfall (0.32 mWE a^{-1} and 360 kg/m^3) is being compressed to an annual layer thickness of 0.42 m and 762 kg/m^3 at 65 m depth. Firn compaction and associated vertical advection profile are therefore consistent with observations.

S.4. Climatic Projections

We interpolate time series of annual SMB simulated by MAR3.5 between 1950–2100 from simulations forced by CanESM2 and NorESM1. These simulations are part of the ensemble used by the IPCC Fifth Assessment Report [*Church et al*., 2013] and fully described by *Fettweis et al*. [2015]. Both the Canadian CanESM2 and the Norwegian NorESM1 are Arctic-optimized global circulation models (GCMs), but they have different sensitivities of temperature and precipitation to climate change. The simulations use historical simulations of each GCM for 1950–2005 and the RCP8.5 climate scenario of each GCM for 2006–2100. Of the four RCP scenarios used by the IPCC, RCP8.5 projects the greatest radiative imbalance by 2100, and may be regarded as a business-as-usual scenario that assumes little deviation from recent trends in anthropogenic emissions [*Cubasch et al*., 2013].

To improve the site-specific accuracy of these projections, we calibrate the SMB simulated by MAR3.5 forced with CanESM2 and NorESM1 with mean SMB reconstructed from ice cores at Camp Century for 1950–1999 [*Buchardt et al*., 2012]. This calibration involves differencing modelled mean SMB from observed mean SMB during the 1950–1999 period and applying the constant offset to all modelled annual SMB values over the entire 1950–2100 simulation period. *Machguth et al*. [2013] similarly calibrate SMB future projections by comparing modelled mean SMB over the historical part of the simulation to mean measured SMB, and then applying a bias correction for the simulation. This approach relies on the assumption that the bias for the historical period is also valid in the future.

This calibration removes systematic biases of –49 and +179 mmWE a^{-1}, respectively, from the CanESM2 and NorESM1 forced SMB simulations (Figure S6). The bias of the CanESM2 forced simulation is relatively small, 15% of measured mean annual SMB, in comparison to the biases for other Greenland regions and GCM-RCM combinations presented in *Machguth et al.* [2013]. This may be interpreted as suggesting that the CanESM2 forced historical simulation somewhat more accurately represents recent SMB at Camp Century than the NorESM1 forced historical simulation. As meltwater runoff has not been observed previously at Camp Century, we cannot similarly calibrate simulated runoff and must use MAR3.5 output values directly. A previous version of MAR has been demonstrated to simulate SMB in runoff-dominated regions of the ice sheet with a root-mean-squared error of 24% [*Vernon et al*., 2013].

Figure S1 – **A:** Construction of cut-and-cover trenches at Camp Century in 1959. **B:** Vertical cross sectional profile of the 21 sequential cuts used to excavate the standard trench depth of the Camp Century tunnel network [*Abele*, 1964]. (US Government Photo and Figure).

Figure S2 – **A:** Surface mass balance in Northwest Greenland during the 1950s (1950-1959) and **B:** 2090s (2090–2099) as simulated by MAR v3.5 forced by NorESM1 under RCP8.5 [*Fettweis et al*., 2015]. Color bars saturate at minimum and maximum values. Blue shading denotes the accumulation area where surface mass balance is positive. **C:** Surface mass balance, and its components, at Camp Century during 1950–2100 as simulated by MAR v3.5 and forced by NorESM1. Dashed line denotes polynomial trend. The CanESM2 simulation is shown in Figure 4.

Figure S3 – **A**: Observed firn density (ρ) profile at Camp Century [*Kovacs et al*., 1969]. **B:** Cumulative water-equivalent (WE) accumulation (*c*) profile. **C**: Firn age (*t*) profile. **D**: Vertical advection rate (*w*) profile.

Figure S4 – **A**: Inferred vertical advection rate (*w*) and firn compaction rate (*f*) profiles at Camp Century. **B:** Cumulative firn compaction rate with depth.

Figure S5 – NASA flight lines in the vicinity of Camp Century between 1993–2014 [*Gogineni*, 2012]. Green lines denote 1993–2009 flights that did not collect UHF accumulation-radar data. Red lines denote 2010–2014 flights that did collect shallow radar data [*Leuschen*, 2014].

Figure S6 – Raw MAR3.5 surface mass balance simulated at Camp Century [*Fettweis et al*., 2015] and SMB calibrated to observed long term mean accumulation at Camp Century [*Buchardt et al*., 2012] under the CanESM2 and NorESM1 RCP8.5 forcing scenarios. Calibration removes systematic biases of –49 and +179 mmWE a^{-1}, respectively, from the CanESM2 and NorESM1 simulations.