Spatial Variability of Snow Stratification in the Absence of Terrain Factors

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Abstract: Instrumentation and methods for measuring snow properties are compared in an investigation of mm to m scale stratigraphy in a snowpack not influenced by topography, vegetation, or a warm and variable ground surface. Field measurements were conducted within a 20 × 20 × 2 m plot at Pika Glacier, central Alaska. The snow was characterized by 600+ point measurements of density, 400+ measurements of temperature, stratigraphic mapping in 19 snow-pits, and by pulse-radar imaging along 20 cross-plot profiles. Density was measured manually and was calculated from electric permittivity, which was determined with a hand-held probe and by radar velocity analysis. Manual measurements of density with stratigraphic mapping in snow-pit walls identified comparatively few layers, suggesting a relatively homogeneous snowpack. Both the permittivity probe and the radar imaging, however, identified a larger number of layers based on density contrasts. An illuminated column of snow revealed extremely complex stratigraphy, with micro layers extending mm in thickness and up to 10 cm in laterally. Despite minor variations in snow properties at the mm scale, major features in the density and temperature profiles were laterally continuous over 10s of m. Radar imaging revealed more distinctive layering in late season snow, but laterally continuous layers throughout the winter snowpack. These observations demonstrate that snowpack stratigraphy is highly dependent upon choice of scale and measurement tool. Moreover, these data provide evidence for spatial homogeneity of snow densification processes where the snowpack is not influenced by local terrain factors.

Keywords: snow stratigraphy, densification, radar, snow-pit, permittivity

1. Introduction

Many of the physical processes occurring in a snowpack are intimately tied to the snow's density. For example, density is an important factor in heat and mass transport: high density favors heat conduction through the ice-grain lattice, while low density favors processes of diffusion and convection (Yosida, et al., 1955; Sommerfield, 1983; Colbeck, 1993). A snow's density also influences its mechanical behavior, since both Young's modulus and viscosity are dependent upon density (Mellor, 1975). The spatial variability of snow density is therefore important to numerous topics related to snow including avalanches (e.g., Birkeland, 2001), snow hydrology (e.g., Horne and Kavvas, 1997), and the transformation of snow to ice (e.g., Alley, 1988).

We define two types of density based on origin: 1) primary, which develops at the snow surface either during deposition or by subsequent reworking from wind; 2) secondary, which evolves in situ subsequent to deposition due to thermo-mechanical processes. Primary density is a function of precipitation rate, size and type of snow crystals, and the packing and disintegration of crystals by wind. Secondary density results from volumetric creep due to normal and shear stresses, and by the linked processes of heat and mass transport.

Topography, vegetation and the ground surface influence both primary and secondary densification leading to spatial variability within the snowpack. During deposition, the interaction between wind and topography results in significant short-length scale variations in snow properties (e.g., Conway and Abrahamson, 1984). Similarly, vegetation adversely effects wind-driven transport and deposition of snow (e.g., Liston and Sturm, 1998). Following deposition, rates of compaction and heat/mass transport may be influenced by vegetation or by local topographic features (i.e., large rocks) via spatial changes in snow depth, areal variability in energy exchange at the snow surface, and by causing local anomalies in heat flow within the snowpack. Moreover, the thermal conductivity and heat capacity of the ground

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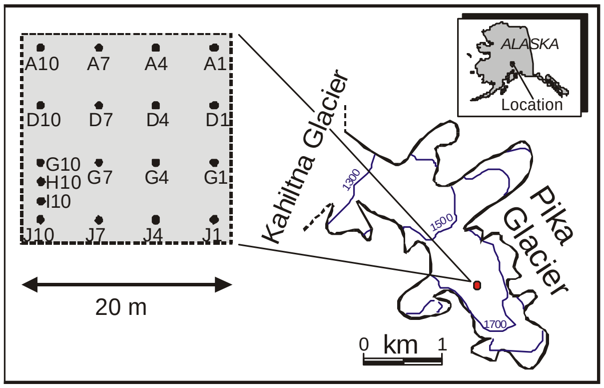

Figure 1*.* *Map of Pika Glacier (contours in meters) and study plot with labeled snow pits.*

itself varies as it changes between rock, soil, or vegetation types. Thus, the heat transfer to base of the snowpack following the seasonal cycle of heat storage and release (e.g., Anderson, 1998), varies spatially beneath the snowpack. The importance of these factors for snowpack properties is demonstrated by Arons et al. (1998) who modeled a two-to four fold increase in the rate of faceting over a rock outcrop as compared to over soil.

Considering the complexity of terrain in mountainous areas, it is not surprising that snow properties have been found to exhibit significant spatial variations at mountain locations (i.e., Conway and Abrahamson, 1984; Birkeland et al., 1995; Birkeland, 2001). Yet, it is not clear how much of the observed spatial variability is attributable to the influence of vegetation, topography, and/or the ground surface, and how much is due to inhomogeneity in thermo-mechanical processes alone. Since thermal conductivity and permeability of snow are strong functions of density, horizontal density variations resulting during deposition could potentially be enhanced by secondary metamorphic processes acting with feedbacks. Further complexity results when the physical properties of a snow cover are affected by both the properties of individual layers, and the sequencening of the layers (Colbeck, 1991). Thus, there is high potential for complex spatial variations in natural snow covers arising simply from randomness in stratification processes.

Here we investigate snow stratigraphy in an alpine environment at the mm-to 20 m length scale. Our objective is to gain insight into the spatial variability of stratification processes, especially densification. In order to isolate these processes, we selected for study a snowpack that was not influenced by vegetation, topography, or a warm and variable basal boundary. The location providing these characteristics was an open site on a glacier surface. The observed spatial changes in stratigraphy at this site represent baseline variability in depositional and subsequent thermo-mechanical stratification processes. An additional objective of this work is to compare tools for measuring snow stratigraphy. These tools include standard snow-pit mapping of stratigraphy, permittivity probe profiling, illumination of a snow column, and radar profiling with a pulse radar system that has not been commonly applied to investigations of snow.

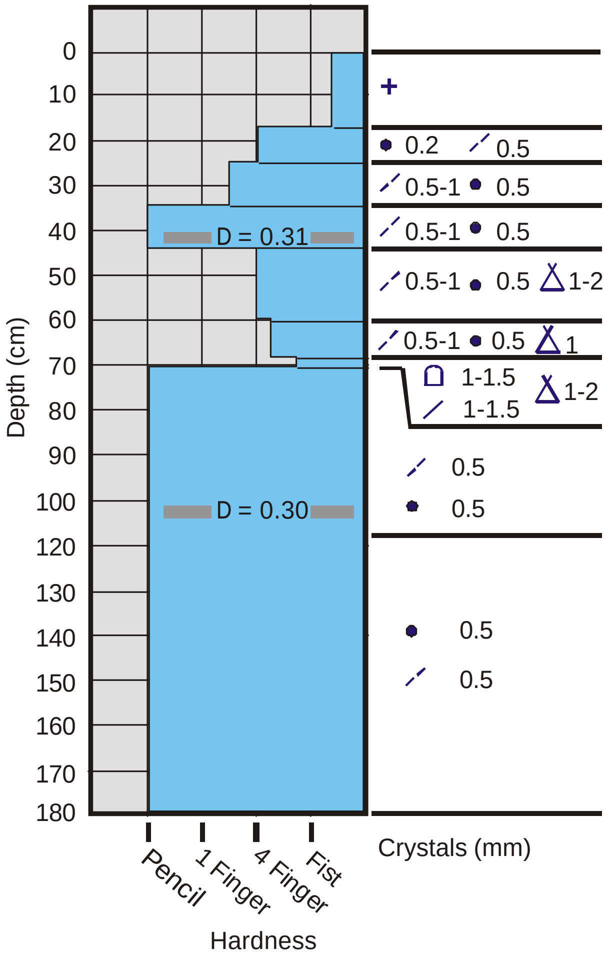

Figure 2*.* *Snow stratigraphy mapped in snow-pit wall based on hardness and crystal type. Manually measured densities (D) shown at two locations. Snow crystals were classified according to international standards (Colbeck et al., 1990). All 19 snow-pits exhibited similar stratigraphy. Snow-pit mapping revealed the lowest level of stratigraphic complexity of the methods employed, but was the only method that identified crystal types included a graupel layer.*

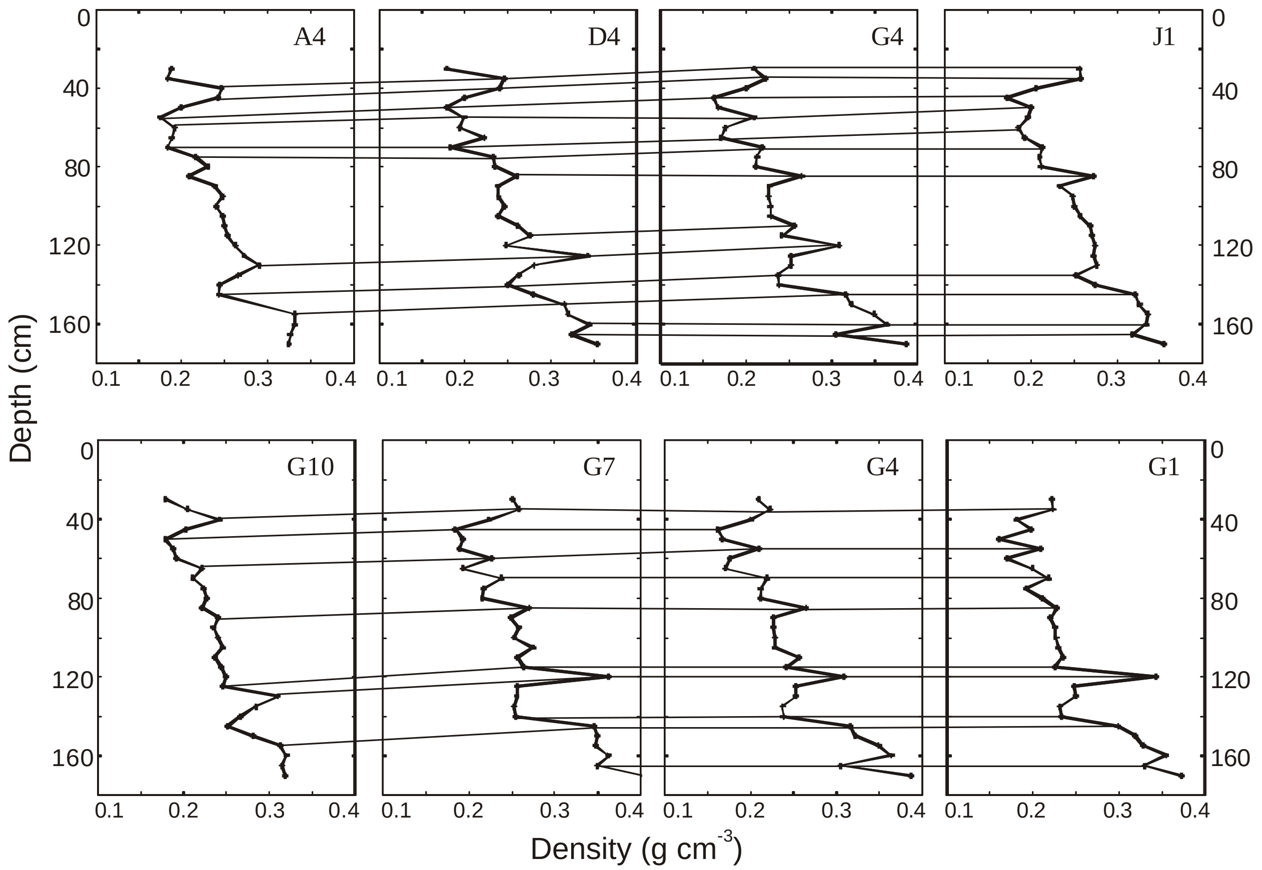

***Figure 3**. Density profiles collected at 5 cm spacing with the permittivity probe. Spacing between pits is 6 m; the top and bottom rows are orthogonal to each other, intersecting at pit G4. Profiles were collected in the snow-pits shown in Figure 1. Tie lines between major density contrasts are shown. Major density contrasts are traceable over the entire study plot.*

2. Data Collection

2.1 Field Site

Data were collected within a study plot located at 1615 m elevation, in the accumulation zone of Pika Glacier, Alaska Range, central Alaska (Fig. 1). The study plot extended 20 × 20 m laterally and from the snow surface to 2-8 m depth. The study region was located near the glacier's centerline in an area where the glacier has no relief and maintains a slope of less than 2 degrees for approximately 1 km along its length. The width of the glacier is approximately 1 km at this location, so the study plot was at least 500 m from any significant topographic feature.

Field work was conducted during the first week of May, 2001, with winter conditions (cold and dry snow) throughout the study period. Approximately 5 m of snow covered the previous summer's snow surface. All data were collected over a three day period, during which some settling occurred in the upper 30 cm of the snowpack. Because snow depths were measured relative to the snow surface, settling caused a discrepancy in the vertical coordinates of data sets collected at different times estimated to be +/- 3 cm.

2.2. Snow-Pit Mapping

Snow-pits 180-200 cm deep were excavated at 19 locations within the study plot. Snow-pits were located on an orthogonal grid with the horizontal spacing between snow-pits no more than 6 m (Fig. 1). The hardness of the snow, the size and type of crystals, and the density were measured by weighing methods in each snow-pit. These data were collected on both a layer-by layer basis, and at 5 cm spacing. Stratigraphic layers were identified primarily by hardness, but also by variations in crystal type. Snow crystals were classified according to international standards (Colbeck et al., 1990). Snow temperature was also measured at 5 cm spacing using a thermocouple array inserted vertically into the snowpack. Repeated density measurements revealed measurement error, believed to be inherent to sampling the 100 cm^3 volume of snow, was about 10%.

2.3. Permittivity Probe

The real and imaginary permittivity and attenuation of snowaround 1 GHz were measured to determine snow density and wetness. The "Finnish Snow-Fork" (Sihvola and Tiuri, 1986) was used for these measurements. This permittivity probe consists of a two pronged wave guide that is inserted into the snow to measure the change in the resonance curve between air and snow. The measurement is based on the real part of the permittivity of snow lowering the resonant frequency, and the imaginary part broadening the resonance curve and increasing signal attenuation at the resonant frequency.

Each of the 19 snow-pits were logged at 5 cm spacing. The sensor averages over a cylindrical volume, with the long axis parallel to the 6 cm length of the prongs, and the radius of influence decaying as 1 over the square of the 1.8 cm separation of the prongs. The resonator was inserted so that the long axis of the measurement was parallel to stratigraphy. Thus, this tool identifies stratigraphy as density contrasts along the digital series of sampled values. In dry snow, the "Finnish Snow-Fork" has been found to yield results that are within 1% of similar dialectic sensors (Denoth, et al., 1984). Error resulting from grain compression as the fork is inserted into the snow is estimated at 1-2% for the density range considered here (Sihvola and Tiuri, 1986). Thus, we believe the densities derived with this instrument are accurate to greater than 5%.

2.4. Pulse Radar

Radar imaging was done with a pulsed radar system using 900 MHz antennas. Ground-penetrating radar is primarily sensitive to contrasts in electric permittivity. In snow, the permittivity depends strongly on the meltwater content and density. The snow in this study was dry so radar imaging reveals stratigraphy as the location of density contrasts within the snowpack.

The antennas were attached to a sled which was pulled by rope from one side of the survey plot to the other. This technique minimized the disturbance of the snow surface. The system was triggered at 10 cm intervals using a string odometer. Data were acquired within the study area along 10 in-line (numbered) profiles, and 10 cross-line (lettered) profiles. The spacing between profiles in both directions was 2 m.

2.5. Illuminated Column

Following the methods of Koerner (1971), a column of snow with dimensions 2 m deep 1 m wide, and 10 cm in thickness was isolated and illuminated from one side. This technique reveals fine-scale stratigraphy, making mm scale features visually identifiable. The column of snow was photographed with a large format camera. The image was then digitized at high resolution (1800 dpi) for computer analysis.

3. Results

Stratigraphy mapped in the 19 snow-pits showed a low level of complexity with little variability across the reach. An example of the mapped stratigraphy is shown in Figure 2. New snow near the surface was relatively soft, but quickly gained "pencil" hardness by 0.75 m. Based on hardness and crystal type, 5-8 layers were typically discernable from the pits. Crystal sizes were less than 2 mm and showed little variability in both the horizontal and vertical directions. In fact, the only difference between stratigraphic layers based on crystal size and type was the presence of graupel in several layers mid-way though the snow-pit. The graupel was abundant enough in one 2-5 cm layer to significantly

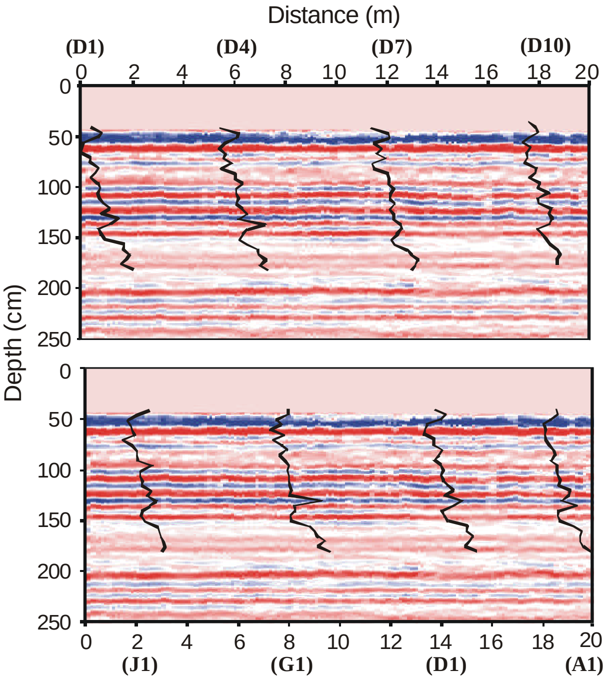

Figure 4. *Radar profiles with overlain density profiles from the permittivity probe. Snow-pit locations shown in parenthesis. Radar shows numerous density contrasts, but little horizontal variability amongst major horizons. The permittivity probe and the pulse radar mapped similar stratigraphy.*

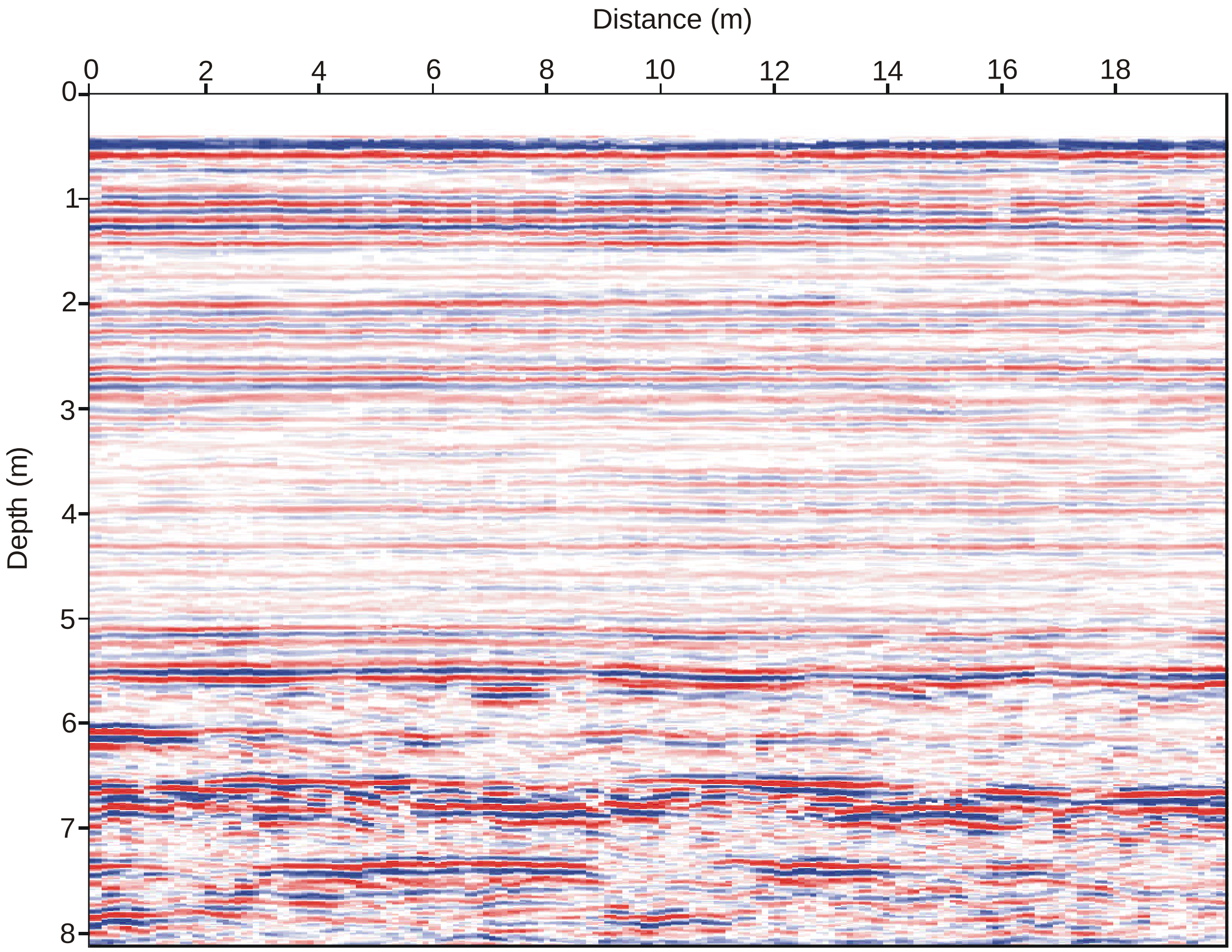

***Figure 5**. Pulse radar profile along line 1 (see Fig. 1). Radar imaging shows numerous stratigraphic horizons with little horizontal variability in the upper 5 m of snow. Region with low amplitude reflections at 3-5 m is early season snow. The previous summer's surface is at 5.5 m; snow stratigraphy shows a high level of lateral variability in the year-old firn (5.5 m and below), probably due to summer melt processes.*

reduce the snow's hardness. The visual observations in snow-pits, however, was the only data collection method that identified this potential weak layer in the snowpack.

Permittivity probe measurements revealed at least twice as many stratigraphic horizons as the snow-pit observations. Figure 3 shows results of density logs measured in 8 snow-pits located along two orthogonal lines. Transitions between layers of the snowpack are revealed by high amplitude inflections in the density profiles. The probe produced a digital sampling of density (5cm spacing), and so errors present in the vertical coordinates introduces complexity in correlating layers between profiles. All of the profiles exhibit a minimum of 10-12 major changes in density. These density contrasts are superimposed on an overall trend of increasing density with depth. Yet, density contrasts are not dampened as higher densities are approached. Good spatial correlation existed between major density contrasts; most were traceable across the entire 20 m study plot. For example, a major inflection in the logs at 120 cm depth is present in every profile except J1. Some low magnitude contrasts are also traceable between all profiles. Furthermore, no profile exhibits a significant level of uniqueness.

The stratigraphy imaged with the radar is similar to that identified by the permittivity probe, but is not complicated by the digital sampling problem. The locations of reflecting horizons generally agrees with density contrasts mapped with the permittivity probe (Fig. 4). Radar profiles show lateral continuity of major boundaries occurred at all depths and throughout the survey area. Some lateral variation in reflection

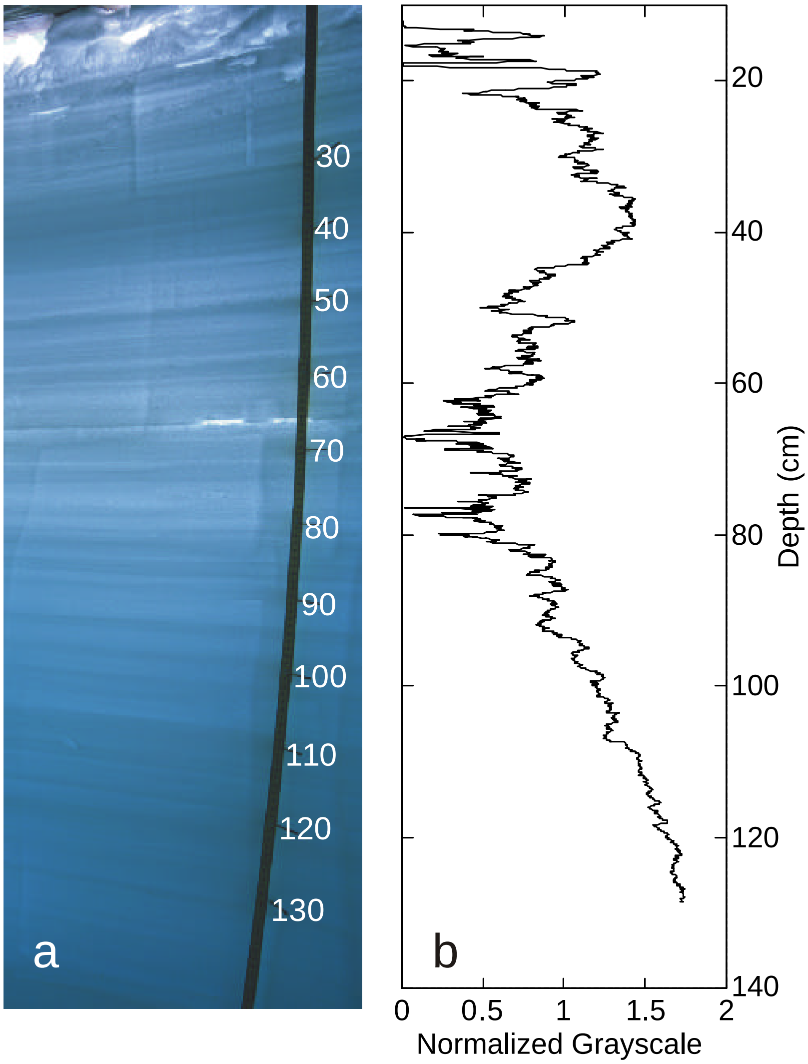

Figure 6. *(A) Photograph of back-illuminated column of snow, with depth shown in cm. Numerous "micro" layers are visible extending mm in the vertical and up to 10 cm in the horizontal. Major stratigraphic layers are in fact composed of multiple micro layers. (B) Grayscale values of digital version of the photograph. Inflection points in curve indicate stratigraphic boundaries; over 1000 boundaries are present in the image.*

amplitude existed, which may indicate subtle changes in density contrast along specific horizons. The radar appears to resolve vertical stratigraphy on a scale of roughly 5-10 cm which is near the theoretical resolution at this frequency. Excellent subsurface penetration is observed with clear reflections to a depth of at least 8 m (Fig. 5). Even at 4-5 m depth where the snowpack is at least 8 months old, strong lateral continuity of layering was present. A region of weaker amplitude reflections existed from about 3 to 5 m depth. This relatively homogenous snow was deposited during the early part of the winter. Below 5 m, greater lateral variation is evident; this is likely the boundary between snow and firn. Other data not presented in this paper suggest the firn transitionally became glacial ice near a depth of 15 m.

The highest level of complexity of the snow stratigraphy is revealed by the illuminated snow column (Fig. 6A). Layers of 1-10 cm thickness were clearly visible extending across the 1 m wide column. In addition, numerous smaller mm thick layers were laterally continuous over 10 cm or less. These "micro" layers formed tangential boundaries with layers above and below, similar to cross-bedding in sedimentary rocks. Close inspection of all thick layers indicated that they were comprised of multiple micro layers. Grayscale values of the photographed column suggests that over 1000 layers are present in the upper 130 cm depth (Fig. 6B). Fourier analysis of the grayscale series identified no frequency to the layering. Finally, a single ice layer 1-3 cm thick and 25 cm wide was present in the column. Ice layers were not observed in any of other 19 snow-pits. The origin of this layer is mysterious as it was completely surrounded by dry snow, and had no vertical conduit connecting it to the surface.

4. Discussion

This snowpack, located in a setting without vegetation, topography, or a warm and variable basal boundary, demonstrated a high level of spatial complexity in the form of micro layering. The cross-bedded contacts between micro layers suggest they were primary features, although it is possible that contrasts between layers were enhanced through secondary densification processes. Micro layer horizons likely represent storm events such as wind gusts, changes in snowfall intensity, or changes in crystal type due to changing conditions in the atmosphere. Assuming a (high) precipitation rate of 2 cm/hr, the stratigraphic column of micro layers represents deposition of approximately 40 layers per hour. This equates to a new visibly distinct layer about every 3 minutes during major snowfall or drifting events.

The macro layering, however, was not complex; the lateral continuity of major layers over distances of 10's of m suggests spatial uniformity of both primary and secondary densification processes. Notably, we found no evidence that micro layers were enhanced by secondary densification processes to produce large contrasts over short distances. In fact, the preservation of micro layers implies that secondary processes do not act quickly to obliterate initial density contrasts. This affirms that the high spatial variability in snow stratigraphy commonly cited is typically due to the influence of local boundary conditions rather than feedbacks between primary and secondary densification processes alone. Hence, a degree of predictability is implied, suggesting that it may be possible to model and assess spatial variability of snowpack stratigraphy in complex terrain, provided the effects of topography, vegetation, and the ground surface can be understood.

The cause of low amplitude radar reflections in early season snow stratigraphy (3-5 m depth) is unclear. Secondary densification processes such as compaction and vapor transport should tend to gradually homogenize the snow with time and depth (Kojima, 1967). The low amplitude region, however, exhibits a relatively abrupt transition to the region of high amplitude reflections; the transition is not gradational as would be expected from secondary densification. A possible explanation is the sudden emergence of the study plot from darkness and shading, partway through the winter. This would imply that sun energy is important in producing stratigraphy at the site, either through production of local katabatic winds and/or heat transfer at the snow surface.

5. Conclusions

The study snowpack exhibited lateral continuity of macro scale (cm thick) layers over a distance of 10s of m and throughout the 5 m depth of seasonal accumulation. These layers were identifiable by a variety of methods, although stratigraphic mapping in snow-pit walls tended to reveal only about half the number of layers other methods did. The continuity of these layers implies that primary and secondary densification processes alone do not cause large density contrasts over short distances. The snow showed a very high level of complexity in micro layering, with mm thick layering extending laterally for up to 10 cm. These layers, which are believed to be primary, numbered over 750 per m. Micro layers were observable in an illuminated snow column, but were not identifiable with radar, a permittivity probe, or by standard snow-pit mapping; hence, the level of stratigraphic complexity is highly dependent upon scale, and upon choice of measurement tool. Our observations show that stratification processes leading to major horizons do not exhibit a high level of spatial variability, implying that these processes are not stochastic, and can be modeled permitted that boundary conditions are accounted for.

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