Annual layers in polar firn detected by Borehole Optical Stratigraphy

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[1] We have developed a system called Borehole Optical Stratigraphy which can detect annual layers in boreholes in polar firn. Borehole Optical Stratigraphy consists of a downhole camera package and post-processing routines, which allow us to measure the intensity of light emitted from an on-board source and returned from the borehole wall. We manually identify the annual layers in this optical signal. We used this system at Siple Dome, Antarctica, in the 2001–2002 austral summer season. Our results agree well with counts of annual layers detected with two different methods in an ice core recovered 50 meters from our borehole. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1694 Global Change: Instruments and techniques; 1640 Global Change: Remote sensing; 0915 Exploration Geophysics: Downhole methods. **Citation:** Hawley, R. L., E. D. Waddington, R. B. Alley, and K. C. Taylor, Annual layers in polar firn detected by Borehole Optical Stratigraphy, *Geophys. Res. Lett.*, *30*(15), 1788, doi:10.1029/2003GL017675, 2003.

1. Introduction

[2] Determining the age of ice at a given depth is fundamental to ice-core research. Many different methods for dating ice cores exist [e.g., *Hawley et al.*, 2002; *Alley et al.*, 1997; *Meese et al.*, 1997; *Steig et al.*, 1998]. Of these, the most detailed record can be obtained by counting annual horizons preserved in the stratigraphy of the ice. These layers can be detected in an ice core by electrical, chemical, isotopic, or physical means [*Meese et al.*, 1997]. We have developed Borehole Optical Stratigraphy, a system that can optically detect annual layers directly on the walls of a borehole. There are significant advantages of such a system; a preliminary depth-age scale can be determined with a few hours of processing in the field, and no core is needed so the procedure can be used in holes drilled with faster non-coring drills as part of site selection for a coring project. We have used this system to date the firn at Siple Dome, Antarctica. Our Borehole Optical Stratigraphy depth-age scale agrees well with those produced by visual observation and Electrical Conductivity Measurement (ECM) analysis of annual layers in a nearby ice core.

2. Borehole Optical Stratigraphy

2.1. Field Measurements

[3] Our Borehole Optical Stratigraphy field system consists of a downhole camera connected to a digital video recorder at the surface. The downhole package is a downward-looking, wide-angle commercial video camera with integrated Light Emitting Diode (LED) scene-illumination lights. Since the camera looks down and has a wide field of view, the entire circumference of the borehole wall can be seen. The depth of the camera is measured by a rotary encoder attached to the sheave wheel over which the cable runs down into the hole; the measured depth is displayed in the video field of view. With a motorized winch, we lower the camera at a constant speed for the entire log. Since the digital video standard takes 29.97 frames per second, we can vary our logging speed to control the depth interval between frames. Typically we collect one image every 1–2 mm, and thus a 100 m borehole takes about 30–60 minutes to log.

2.2. Post-Processing

[4] The resulting log is a recording of the borehole wall covering the entire depth of the hole, with depth information incorporated. To detect annual layers, we process this motion picture to produce an optical "brightness" value for each depth. To get a brightness for each frame of the video, we take an average of the pixel values in an annulus around the borehole wall. The depth is read from the image using optical-character-recognition software. The result is a brightness vs. depth record. A representative short section of one such log is shown in Figure 1.

2.3. Source of Brightness Variations

[5] The variations in brightness seen in Figure 1 most likely result from the same subtle differences in grain size, bubble size, and density that allow the visual identification of annual layers in ice cores. Repeat logs of the same hole (Figure 2, panel a) show the same features from one log to the next. "Blank" tests (logs with a hood placed over the camera and light source, isolating them from the environment) indicate that the source light on the camera is very stable and could not be responsible for the variations we see. Tests of the distribution of brightness around the annulus (Figure 2, panel b) show that we are seeing near-horizontal layers and not isolated bright spots in the wall.

3. Visual Stratigraphy

[6] Analysis of visible structures in ice cores is one of the oldest techniques in ice-core studies. Many different structures can be visually identified in a core. Annual-layer counting by visual means is based on differences in appearance of summer and winter snow. In shallow firn at Siple Dome, the most prominent annual stratigraphic marker is the "depth hoar/wind slab couplet", consisting of course-grained depth hoar, formed in the summer when strong temperature gradients promote grain growth in the snowpack, overlain by a fine grained, wind-packed layer formed in the winter [*Alley*, 1988; *Alley et al.*, 1997]. Visual

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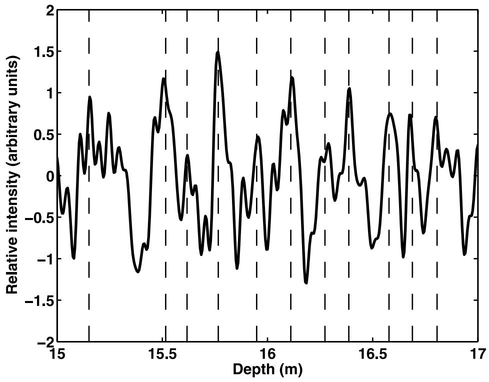

Figure 1. Band-pass filtered Borehole Optical Stratigraphy signal (heavy solid line) and the depths of "Annual Layer" picks (dashed lines). The band-pass filter passed fluctuations of 1 to 50 cm wavelength. Peaks in brightness were chosen as the "Annual" markers.

stratigraphers also note occasional melt layers in cores. Some melt layers were identified at Siple Dome, but are infrequent and were indistinguishable in the borehole log. Dust concentration has been measured with optical methods, both in cores and in deeper ice [*Ram and Koening*, 1997; *Bay et al.*, 2003]. We did not see dust layers in our logs at Siple Dome, nor did visual examination of the core identify major visible dusty horizons in the depth interval of the borehole observations. Mechanical marks left on the borehole walls by the drill could potentially affect our measurement, by changing the angle of incidence and thus the scattering properties of the wall. In practice, a gouge in the wall from the drill is likely to be more striking, with a sharply defined edge, than the more smoothly varying features we see in the log. Presumably such marks would also be visible and identifiable in the raw log footage, and no such marks were seen. Although we cannot exclude the possibility that "drill scarring" could affect our signal, these characteristics indicate that any artifacts caused by drilling are likely to be small.

4. Analysis

[7] Once the Borehole Optical Stratigraphy log has been processed and a brightness profile produced, we must identify the annual layers. One option is to visually examine the record and hand pick peaks or troughs. We suggest that peaks in brightness correspond to zones of fine-grained snow or firn that cause increased backscatter of light to our instrument [*Wiscombe and Warren*, 1981]. These zones are the "wind-slab" component of the annual "depth hoar/wind slab couplet" that forms the basis for annual layer stratigraphy. Our approach is to first band-pass filter the data, to eliminate oscillations shorter than 1 cm or longer than 50 cm, and then to visually pick the significant peaks. In practice, our continuous log was broken up into a series of ≈5-meter sections because there were metal markers in the hole at these intervals [see *Hawley et al.*, 2002; and Hawley et al., Vertical strain measurements in firn at Siple Dome, Antarctica, *Journal of Glaciology*, in review, for a discussion of those markers]. We interpolated layers across the ≈50 cm data gaps left by the metal markers. The resulting depth-age scale is shown in Figure 3. Also shown for comparison are 2 other depth-age scales determined by annual-layer counting in the SDM-A core, ≈50 meters away. The Pennsylvania State University (PSU) team visually examined the core and identified annual horizons. The Desert Research Institute (DRI) team used a computer algorithm [*Taylor et al.*, 2002] to identify annual cycles in electrical conductivity records on the core. All agree within ≈10 percent.

5. Discussion

[8] The identification of annual layers is generally considered to be difficult, and there are often differences between observers for a given section of core. Sometimes the same observer can obtain different layer counts on the

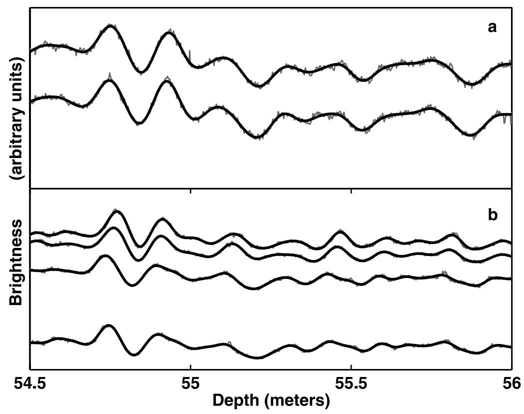

Figure 2. Panel (a) Repeat logs of the same hole, taken one day apart. Clearly we are seeing the same features. Panel (b) A third log of the same hole, with the annulus divided into four quadrants, each averaged and plotted separately. The correlation indicates that the features are near-horizontal stratigraphic layers in the walls of the borehole.

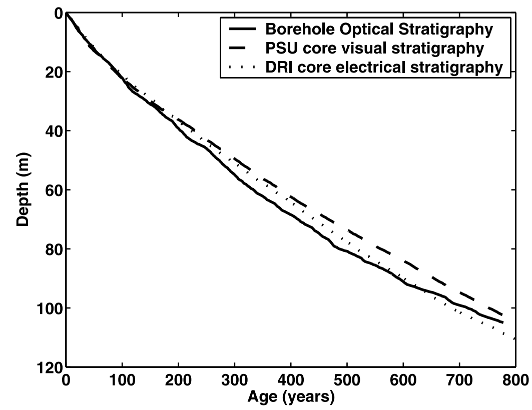

Figure 3. Depth-age profiles at Siple Dome from annual-layer counting. The solid line is from layers manually counted with Borehole Optical Stratigraphy. The dashed line is from layers in a nearby core counted visually by PSU. The dotted line is also from the nearby core, but used the DRI autopicker to count layers in the ECM record.

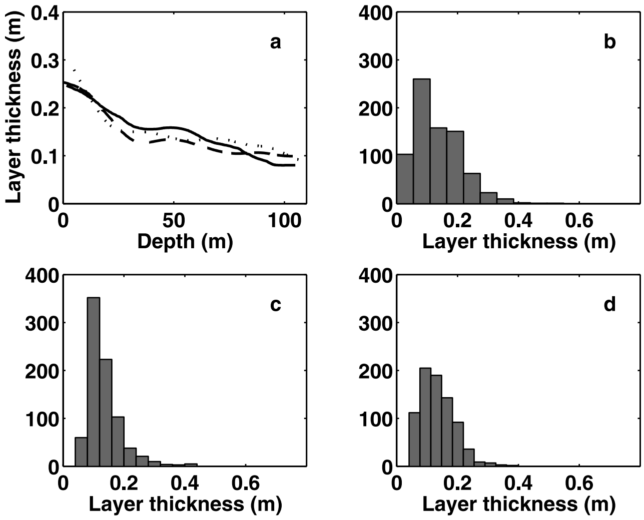

Figure 4. Comparisons between layer-counting methods. Panel (a) smoothed annual layer thickness vs depth showing reasonable agreement among three methods of determining annual layers: Borehole Optical Stratigraphy (Solid curve), visual stratigraphy on the core (dashed curve), and electrical stratigraphy on the core (dotted curve). Panels (b–d) histograms of the layer thickness determined by Borehole Optical Stratigraphy, PSU visual stratigraphy, and DRI electrical stratigraphy, respectively.

same section of core when counting on different days. Accuracy of annual layer counting by visual means depends on accumulation rate and other factors, with errors ranging from ≤1% to many percent or more [*Alley et al.*, 1997; *Taylor et al.*, 2002]. With its relatively low accumulation rate, Siple Dome is unlikely to yield ≤1% accuracy, as witnessed by the differences between the PSU and DRI curves in Figure 3. Owing to spatial variability in formation of annual layers [*Alley*, 1988], and to the possibility that slight core loss during recovery affected subsequent observations, we do not expect exact correspondence between layers identified visually or in other ways on the core, and layers observed in a borehole ≈50 m away. As an alternative measure of our success in detecting annual layers, Figure 4 compares the thicknesses of annual layers detected by the three methods. Panel a shows that manually picked layers from Borehole Optical Stratigraphy match the smoothed layer thickness vs. depth curves from visual stratigraphy and electrical stratigraphy well. Near the bottom of the profile Borehole Optical Stratigraphy appears to contain slightly thinner layers on average than the other methods, and this effect can be seen in the accompanying histograms. If this is anything more than a difference between observers, it could result from decreasing contrast at greater depths, which makes individual layers more difficult to identify. A future logging tool might overcome this limitation by having an adjustable light source to improve the signal strength at greater depths. The histograms show that although the PSU visual stratigraphy has the lowest standard deviation, the range of layer thicknesses is similar among all three methods. This gives us greater confidence in our ability to detect annual layers.

6. Conclusions

[9] Borehole Optical Stratigraphy can be used to quickly determine a depth-age relationship for polar firn. Our depth-age relationship derived by counting annual layers on a borehole wall is very close to those derived by other observers counting layers in a nearby ice core. The unique ability to detect annual layers in a borehole makes Borehole Optical Stratigraphy a valuable tool for ice-sheet dynamics and ice-core paleoclimate studies. Using Borehole Optical Stratigraphy for annual-layer detection in the future could allow rapid characterization of large areas during ice-core site selection. For example, by placing absolute dates on the layers detected by Ground Penetrating Radar, we could infer temporal and spatial variability in accumulation rate over a large region.

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