

A deep high-resolution optical log of dust, ash, and stratigraphy in South Pole glacial ice

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[1] We describe a new dust logger designed to operate in water-filled IceCube boreholes in South Pole ice, and we give examples of its performance. We recorded optical effects due to bubbles, dust, and volcanic ash in situ from ~ 70 to 2100 meters. Seasonal layering in bubble concentration could also be discerned. Below ~ 1300 m over the interval 25 ka to 70 ka, because of the conversion of all air bubbles to invisible hydrate crystals, and the close match between refractive indices of the surrounding ice and the water in the borehole, scattering from dust provided fine-structure in the depth-dependence of concentration with a resolution of <1 cm. Thin, highly absorptive horizons in the data set confirm there is significant fallout at South Pole of ash from explosive volcanic events. By locating and dating volcanic ash layers in the South Pole dust record, it may be possible to match them to volcanic layers found across Antarctica and in Greenland. **Citation:** Bramall, N. E., R. C. Bay, K. Woschnagg, R. A. Rohde, and P. B. Price (2005), A deep high-resolution optical log of dust, ash, and stratigraphy in South Pole glacial ice, *Geophys. Res. Lett.*, *32*, L21815, doi:10.1029/2005GL024236.

1. Introduction

[2] The AMANDA telescope (Antarctic Muon and Neutrino Detector Array) at the South Pole has by far the largest collecting power of any high-energy neutrino observatory and has recorded the greatest number of upward-going, high-energy neutrino events. The detector consists of a three-dimensional array of 677 photomultiplier tubes housed in pressure vessels at depths from ~ 1500 to ~ 2000 m and cabled to the surface on 19 vertical strings. The instrumented volume of ice is ~ 500 m in height and 200 m diameter, but the effective volume used for neutrino detection is considerably larger as a consequence of the long optical absorption length. The present study is part of the IceCube collaboration's efforts to install 80 new strings and expand the effective volume to ~ 1 km³. Key to the success of AMANDA was the use of optical fibers, LEDs and lasers for the purpose of measuring optical transparency of the ice as a function of wavelength. The distributions of arrival times of nanosecond light pulses emitted from one light source and received by optical modules at distances up to ~ 200 m away were analyzed and used to measure separately the absorptivity and scattering coefficient as a function of wavelength and depth. A few optical modules above and below the 1500 to 2000 m depths were used to study optical properties of ice but not to detect neutrinos. Because

of the relatively narrow cylindrical shape of the AMANDA array and the relatively flat bedrock, with typical vertical variability of 10–30 m, the optical properties of the ice were assumed to vary only with depth within the active volume. Figure 1b shows, for one wavelength, the scattering coefficient as a function of depth found by AMANDA (M. Ackermann et al., Optical properties of deep glacial ice at the South Pole, submitted to *Journal of Geophysical Research*, 2005). At depths in South Pole ice shallower than ~ 1300 m, scattering by air bubbles dominates scattering by dust, including most of the dust peak corresponding to the Last Glacial Maximum (LGM). At depths greater than ~ 1300 m, the bubbles have converted to air clathrate crystals [Price et al., 2000], leaving a clearly visible dust signal. Because air bubbles scatter light without absorbing it, analysis of absorption as a function of depth showed a strong peak at a depth of 1300 m corresponding to the LGM. Figure 1a shows the relevant dust peaks at Vostok [Petit et al., 1999], obtained using Ca²⁺ concentration as a proxy for dust. A rough age versus depth relationship for South Pole ice for the last 70 ka (kiloyears before present) was obtained by Price et al. [2000], who identified the peaks at LGM, A, B, C, and D with the Vostok ages at the corresponding peaks and included the age versus depth relationship obtained from analysis of a 200-m South Pole core [Hogan and Gow, 1997]. The dust peaks determined by AMANDA were averaged along light paths of ~ 20 –100 m, and the dust (Ca) at Vostok was sampled at intervals of 15–25 m in depth in an ice core.

[3] In the expansion from AMANDA's active volume of ~ 0.03 km³ to IceCube's active volume of 1 km³, variations in optical properties in horizontal as well as vertical directions will have to be measured. Judging from the vertical structure in the radar profile [Blankenship and the Instrument Definition Team for a Europa Radar Sounder, 2001] of ice down to bedrock in the vicinity of South Pole (~ 2820 m), isochrons of constant optical absorptivity and scattering vary in depth by ~ 50 m over a square kilometer. Applying the AMANDA method of recording the arrival time distribution of light pulses from LEDs and lasers within the IceCube array, with its 4800 optical modules (80 strings; 60 modules per string) will be costly and time-consuming and limited in depth resolution by the spacing of the modules on the strings. As a complement to this technique, we plan to mount dust loggers on at least 10 of the 80 IceCube strings to be deployed in the next five years and to read the dust record with ≤ 1 cm resolution as the string is lowered in the meltwater in the borehole. Correlating peaks and valleys in the records across the IceCube array will enable us to generate isochrons of constant optical

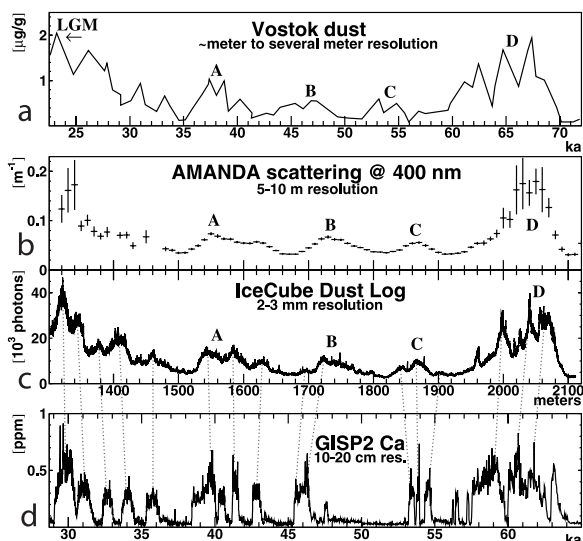


Figure 1. Comparison of dust (a) measured in a Vostok ice core with a Coulter counter; (b) inferred from travel time of light from emitters and receivers in the AMANDA array in South Pole ice; (c) measured in the present experiment with a new dust logger in a water-filled IceCube borehole; and (d) inferred from analyses of calcium ions in the GISP2 ice core. The dashed lines are drawn only to guide the eye in suggesting tentative associations and are not meant to imply simultaneity.

properties for use in reconstructing tracks of muons resulting from neutrino interactions in ice.

[4] In this paper we describe a dust logger with improved design that was deployed in a borehole with the first IceCube string in January 2005, and we show examples of its applications to climatology. The quality of the data exceeded our most optimistic expectations.

2. Method

[5] The new dust logger designed for IceCube, shown in Figure 2, replaces focused LEDs [Bay *et al.*, 2004] with a 404-nm laser line source emitted horizontally in a 90° fan pattern ~ 2 mm thick, which is paired with an integrated photomultiplier tube and digital photon counter for light detection. For deployment on the first IceCube string, armor sections were added to protect the glass windows of the instrument while lowering it down the 2450 m hot-water-drilled borehole. The logger telemetered data from depths down to ~ 2150 m before communication was lost. Data were taken as 10-ms samples and sent to the surface at ~ 50 Hz on an optically-isolated differential serial link to a dedicated laptop computer.

[6] The instrument measures the light from a source pointed into the ice surrounding a glacial borehole [Bay *et al.*, 2001; Miočinović *et al.*, 2001; Bay *et al.*, 2003]. Care must be taken to ensure that sideways-directed photons exit the borehole efficiently, where they scatter off bubbles and both scatter and absorb on dust and volcanic ash in situ. The fraction that is transmitted through intervening strata and then scattered back into the borehole and detected, in a phototube masked from direct access to the light beam, faithfully represents the record of past changes in atmo-

spheric impurities [Mayewski *et al.*, 1997; Bay *et al.*, 2003]. Resolution is primarily determined by collimation and focusing of the light source onto a region just beyond the fluid/ice interface, but signal quality can also be affected by the optical match between the borehole fluid and ice, as well as the verticality and wall smoothness of the borehole. Black nylon brushes intercept photons scattered within the borehole that have by-passed transmission through the external ice and would otherwise contaminate the signal and spoil contrast. The brushes also sweep detritus from the fluid which might occlude the source beam. The intensity of the light source is adjustable from the surface for changing conditions.

[7] Photon counts were correlated with depth information provided by high-precision pressure sensors mounted near the instrument. Although the logger resolves adjacent horizons with subcentimeter precision, absolute depth determination was limited to a meter or more by the accuracy of the pressure sensors, measurement of the water level from the snow surface, and a correction for the compressibility of the water column.

3. Results

[8] Figure 1c shows the high-resolution signal from the IceCube dust logger for the age interval ~ 25 to ~ 70 ka. For comparison, in Figure 1c are shown the Vostok dust record, the scattering versus depth measured by light emitters and photomultiplier tubes on AMANDA strings in ice at the South Pole, and the GISP2 calcium record [Mayewski *et al.*,

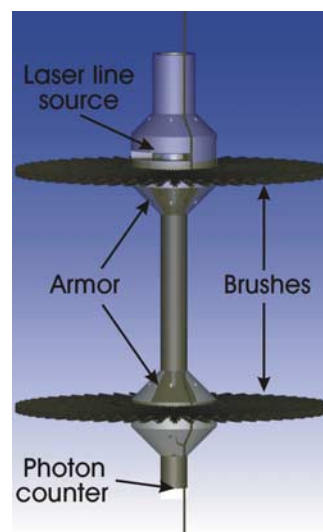


Figure 2. Sketch of dust logger immersed in water-filled borehole in South Pole glacial ice. Light is emitted in a horizontal fan, enters the ice and interacts with bubbles, dust, or volcanic ash, and a fraction of it reenters the borehole and is detected in the downward pointing photon counter. The steel support cable is snug against the central cylindrical vessel; the cable for telemetry and power is not shown. The instrument has a height of 80 cm. The IceCube borehole, not shown to scale, varies in diameter from ~ 60 to >90 cm. Improvements in the hot-water drill will make it possible to control diameter at ~ 60 cm in future IceCube boreholes.

1997] for the same time interval. The resolution of the new dust logger allows it not only to reproduce the major features in the Vostok and AMANDA records but also to show subpeaks that were never previously resolved and fine-structure within those subpeaks which suggest that the abrupt climate changes characteristic of the Greenland record are also present, though subdued, in the East Antarctic [Bender *et al.*, 1994].

[9] Figure 3 shows an expanded region of the IceCube record at a shallow depth where bubbles dominate. The oscillatory pattern is consistent with seasonal modulation of bubble concentration, as observed in an ice core by J. Fitzpatrick (private communication, 2003) and discussed by M. K. Spencer *et al.* (unpublished manuscript, 2005). Correcting the horizontal scale for the density of firm ($\sim 740 \text{ kg/m}^3$ at 83 m [Kuivinen *et al.*, 1982]), this part of the record gives an average annual layer thickness of $\sim 110 \text{ kg m}^{-2} \text{ yr}^{-1}$ at an age of ~ 600 years, consistent with visual counts of annual layers [Hogan and Gow, 1997].

[10] Figure 4 shows an example of the signature [Bay *et al.*, 2001] from a thin, highly absorbing volcanic ash layer in transmission, detected at around 300 m depth. We also found strong volcanic signatures near 700 and 1000 m, as well as several other weaker signals. These horizons confirm that substantial ash deposition at South Pole from distant explosive volcanic eruptions is not uncommon. The deep, narrow dip is delineated by ~ 40 data points with very little scatter and is evidence for mm-scale resolution of the sharpest horizons.

4. Discussion

[11] Compared with the earlier versions [Bay *et al.*, 2001, 2003, 2004], the new dust logger in IceCube has two advantages: a mm-scale horizontal fan beam of laser light gives sharp depth resolution, and liquid water in the borehole with refractive index that matches that of ice better than organic drilling fluid and eliminates scattering at the fluid-ice interface. Both the data and Monte Carlo simulations for this logger confirm that mm-scale resolution is technically achievable, however, misalignment, intrinsic

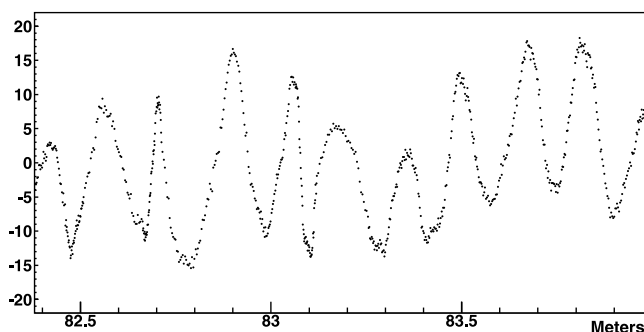


Figure 3. Sample of data showing seasonal peaks in bubble concentration. For a density of 740 kg/m^3 at this depth in South Pole ice, the accumulation rate is $\sim 10.6 \text{ g cm}^{-2} \text{ yr}^{-1}$. Although the annual signal may be reliable over short time intervals, frequently poor optical contrast between seasons, erratic accumulation and post-depositional perturbation are expected to confound dating based solely on layer counting.

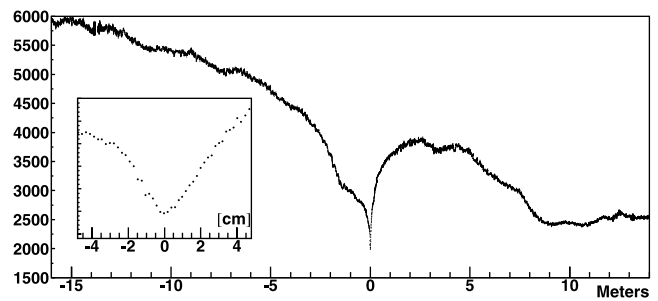


Figure 4. A volcanic ash layer near 300 m depth, shown at two different depth scales. Taking into account that an ash layer is several mm to $\sim \text{cm}$ in vertical thickness, we see from the blowup of the cusp (inset) that the achievable local resolution is no worse than a few mm.

lateral variations of ice features, limited sampling rates and cable vibrations can mask subtle features, particularly those much finer than 1 cm. In Greenland (to be published), the laser source has proven considerably more useful in resolving ash layers in ice below the bubbly region, where absorptive horizons present a less pronounced signal.

[12] The high resolution of this new dust logger may help answer remaining questions surrounding rapid climate change seen in the East Antarctic, as well as the synchronicity between polar records. Advances in the use of synchronous atmospheric methane and O_2 -isotopic anomalies in both Greenland and Antarctica have permitted cross-dating between hemispheres to within a few centuries [Bender *et al.*, 1994; Blunier *et al.*, 1998; Blunier and Brook, 2001; Brook *et al.*, 2005]. If volcanic ash layers in the IceCube record can be matched to similar layers observed elsewhere in Antarctica, then it should be possible both to identify fixed reference times and to track changes in ash deposition across the continent. In the future we should be able to extend dust logger records to the bottom of the deepest IceCube boreholes, beyond 2400 m, corresponding to an age of ~ 100 ka.

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