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Climate logging with a new rapid optical technique at Siple Dome

Ryan C. Bay, P. Buford Price

Physics Department, University of California, Berkeley, CA 94720

Gary D. Clow

U.S. Geological Survey, Lakewood, CO 80225

A. J. Gow

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755

Abstract. The dust logger design is based on a decade of experience in the use of light sources to measure optical properties of deep Antarctic ice. Light is emitted at the top of the instrument by side-directed LEDs, scattered or absorbed by dust in the ice surrounding the borehole, and collected in a downhole-pointing photomultiplier tube (PMT) a meter below. With this method the ice is sampled at ambient pressure in a much larger volume than is the case in a core study, and the entire length can be logged in one day. In ice in which scattering is dominated by bubbles, the absorption from dust impurities is perceived as a drop in signal, whereas in bubble-free ice the scattering from dust increases the light collected. We report on results obtained in Siple Dome Hole A in December 2000. The instrument measured increases in dust concentration extending over many meters during glacial maxima, as well as narrow spikes due to ~ 1 cm thick ash and dust bands of volcanic origin. Monte Carlo simulation is employed to clarify data analysis and predict the capabilities of future designs.

Motivation

The recognition that humans are impacting the earth's atmosphere has stimulated international efforts to understand the earth's climate history more fully. Records of paleoclimate from polar ice cores provide the most direct and best-resolved view of variations in atmospheric composition and climate over the past 420,000 years [*Petit et al.*, 1999]. Polar ice also holds a record of atmospheric processes [*Alley et al.*, 1993; *Mayewski et al.*, 1997], of past volcanism [*Zielinski*, 2000], of other environmental changes [*Saltzman et al.*, 1997], of extraterrestrial dust flux [*Brook et al.*, 1998], and of solar and geomagnetic variability [*Finkel and Nishiizumi*, 1997; *Stuiver and Braziunas*, 1998].

Paleorecords reveal three modes of climate variability on time scales less than 10^6 yr. The first involves growth and decay of large ice sheets and sea level changes on 10^4 to 10^5 yr timescales. These are commonly attributed to the complex interplay of Milankovitch forcing (a hypothesis that the Earth's climate is controlled by variations in incoming solar radiation tied to subtle yet predictable changes in the Earth's orbital eccentricity, tilt and precession) and internal earth-system feedbacks. The second mode of variability – Dansgaard-Oeschger or stadial/interstadial events [*Dansgaard et al.*, 1993; *Bond et al.*, 1993] – refers to extremely rapid warmings and coolings and subsequent warm and cold periods of 500 to 4000 yr duration. They are best known from the last glacial period (20,000 to 110,000 yr B.P.), but may extend into the Holocene [*Alley et al.*, 1997; *Bond et al.*, 1997]. The third mode of climate oscillations, on still shorter timescales, involves a number of types of behavior ranging from the well-known El Nino Southern Oscillation to century-scale climate variability [*Hunt*, 1998] that may be related to solar variability [*van Geel et al.*, 1999; *Stuiver et al.*, 1995].

There is long-standing interest in causes of time-variability of the radiocarbon record [*Damon and Sonett*, 1991]. The record contains suggestions of numerous periodicities including $\sim$2300, $\sim$208, $\sim$88, 22, and 11 yrs. Some of the variability may be due to changes in the terrestrial magnetic dipole moment, but some appears to be due to periodicities in the solar activity or a combination of solar forcing and oceanic response. Mechanisms for a solar origin of these periods are not understood. It is known that the sun, through the solar wind, modulates the intensity of cosmic rays. One hypothesis holds that cosmic rays affect global cloudiness and temperature [*Svensmark*, 1998; *Svensmark and Friis-Christensen*, 1997] and may lead indirectly to variations in dust concentration in ice cores.

An important question in volcanology is whether there is a climate-forcing contribution. Another is the geographic extent over which emissions are found, especially the extent of diffusive transport of granular material as a function of particle size and latitude, such as from one hemisphere to the other [*Langway et al.*, 1995; *Palais et al.*, 1992]. Deep ice cores from polar regions appear to be an ideal medium from which to extract lengthy, high-resolution records of past volcanism [*Gow and Williamson*, 1971]. Volcanic signals are often used as an age vs. depth calibration, and with some development this technique could be extended further back in time.

Soot concentration in ice cores might be a tracer of global fire frequency and aridity, which depends on global temperature. However, because of its low concentration, errors are large and no correlation has yet been demonstrated. Wol-

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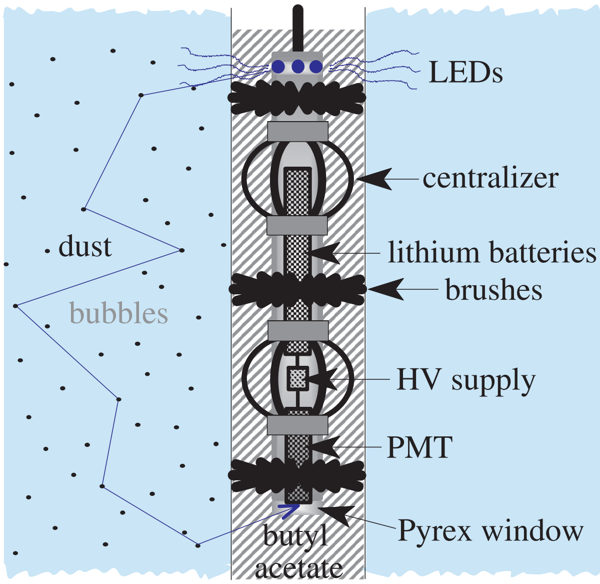

Figure 1. Principle and design of Dust-logger-I.

bach et al. found that Cretaceous-Tertiary (K-T) boundary clays from various sites are enriched by a factor of up to 3×10^5 in soot, which apparently came from a global fire triggered by an asteroid-size object with impact energy 10^8 to 10^9 Megatons [*Wolbach et al.*, 1998]. This is the now famous object widely believed to have led to the great K-T mass extinction. The densest soot layer, < 0.3 cm thick, coincides with an Ir-rich layer, supporting the view that the fire was triggered by asteroidal impact. It would be of great interest to be able to obtain evidence for additional events, to accurately date them, and to search for correlations with extinctions of species on a smaller scale than at the K-T boundary.

Principle and design

The dust logger is a byproduct of years of experience in the use of light sources by the AMANDA collaboration (Antarctic Muon and Neutrino Detector Array) to measure optical properties of deep Antarctic ice [*Askebjer et al.*, 1997; *He and Price*, 1998]. Emitters and receivers buried at depths of $\sim$1 to $\sim$2 km in ice and at lateral distances of $\sim$0.1 km probe the scattering and absorption of light by air bubbles and dust grains. The dust logger compresses this instrumentation from a volume of $\sim$0.1 km^3 into a compact device that fits into a borehole. A light source shines into the ice surrounding the borehole; photons scatter off of bubbles and dust, some are absorbed on dust, and a small fraction are detected in a downward-looking PMT below. In ice in which scattering is dominated by bubbles the absorption from dust impurities causes the signal to drop, whereas in bubble-free ice the scattering from dust increases light collection (in the Siple Dome borehole, scattering is dominated by bubbles all the way to bedrock).

Recent simulations verified that the dust logger concept is a very promising one [*Miocinovic, Price and Bay*, 2001]. In contrast to a core study, a larger volume of ice is sampled at ambient pressure and an entire borehole can be logged in one day. Coring has the advantage of providing samples for laboratory analysis of gases, isotopes, chemistry, and particulates.

Dust-logger-I (Fig. 1) consists of three radial 370 nm LEDs (Nichia NSHU550E) 120° apart, one meter above a downward-looking PMT (Hamamatsu R6094). Centralizers keep the optics steady, and black 1”-thick nylon brushes slightly wider than the hole seal out light scattered within the borehole and ensure that photons reaching the PMT have sampled the exterior ice (this can also be accomplished with a pulsed source and electronics). The entire unit is constructed from black oxidized stainless steel pipe. Light is transmitted through Pyrex glass windows sealed with o-rings. The device is tethered and controlled via a 4-conductor logging cable. The LEDs are powered from a current supply at the surface through one of the conductors pairs. A miniature high voltage supply for the PMT is powered by on-board lithium-oxyhalide batteries designed for large capacity at cold temperatures. The third wire is used to control the output of the HV supply, and the fourth returns the output current of the PMT anode. The armor of the cable is employed as a fifth conductor for signal and HV-control ground. The PMT output current is dumped across a selectable parallel RC circuit and unity gain amplified and inverted at the surface. This signal voltage is recorded every 10-40 cm by an ADC connected to a laptop computer. For each voltage measurement, the computer also queries an optical payout encoder on the winch and records depth. This depth is later corrected for cable elongation so that the readings are accurate to $\pm$2 m.

Results at Siple Dome

Figure 2 shows the raw signal taken in December 2000 with Dust-logger-I in the 1000-m Siple Dome Hole A. The top curve is the signal while logging downhole; the bottom curve is taken while logging uphole when the bottom set of brushes are swept downward, obscuring the PMT. The signal drops gradually with depth as scattering from bubbles decreases with growing hydrostatic pressure. Monte Carlo simulation (Fig. 3) verifies that the recurrent, narrow, two-pronged spikes are to be expected when the logger encounters highly-absorbing layers localized to $\sim$1 cm thick, such as those resulting from nearby volcanic eruptions. One of us (AJG) visually confirmed the volcanic ash depositions over the portions of the archived ice core which remained sufficiently intact. Some 35 layers are clearly discernible over the length of the borehole and are listed in Table 1.

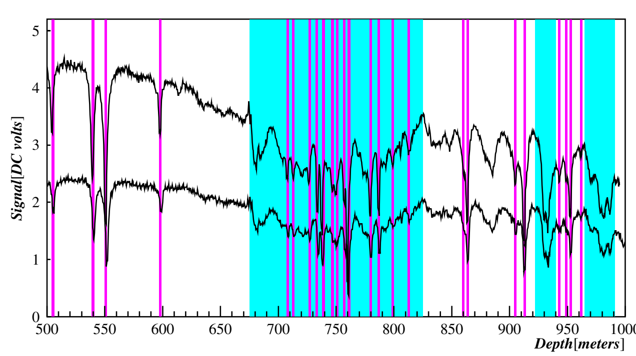

Figure 2. Raw data taken in Siple Dome Hole A. Vertical lines designate sharp spikes due to thin highly-absorbing layers, most of volcanic origin. The shaded regions are long-term climatic changes.

Broad depressions in the signal extending over many meters correspond to two long-term climatic changes, the LGM between ~675–825 m and the 65-kyr peak seen in the dust record at depth ~930 m. By removing the ash spikes and inverting the ordinate to aid the eye, the variations can be related to corresponding episodes at other locations (Fig. 4). Using isotopic studies of $\delta^{18}O$ of O_2 (B. Barnett and M. Bender, *private communication*, 2001) to convert depth to age, the signal can be compared directly to the dust profile taken from the core at Vostok [*Legrand et al.*, 1988]. The LGM and 65-kyr peak agree very well, but the feature between 965–990 m at Siple Dome (centered at ~100 kyr in Fig. 4*a*) is not present in Vostok data (Fig. 4*c*). This leads us to consider extending the age of the ice near bedrock at Siple Dome out to 170 kyr in order to associate this feature with the Penultimate Glacial Maximum (PGM). The resulting chronology is difficult to reconcile with the $\delta^{18}O$ data, and it may be that the absorptive feature near bedrock at Siple Dome is a result of entrapment of subglacial till in folding of the bottom-most layers.

An irregular feature near the end of the LGM (clearly seen in Fig. 2 at ~680 m) exemplifies a "backboard" effect familiar from Monte Carlo studies: the signal increases near 675 m, just before decreasing to a minimum near 681 m. A sharply-defined layer of increased scattering can act as a waveguide and direct photons into the detector, *increasing* the signal as the logger approaches. Our simulations show the anomaly to be consistent with an increased dust concentration of a factor of a few over ~6 m, which could result from a sustained hiatus in snow accumulation as postulated by Alley (*private communication*, 2001).

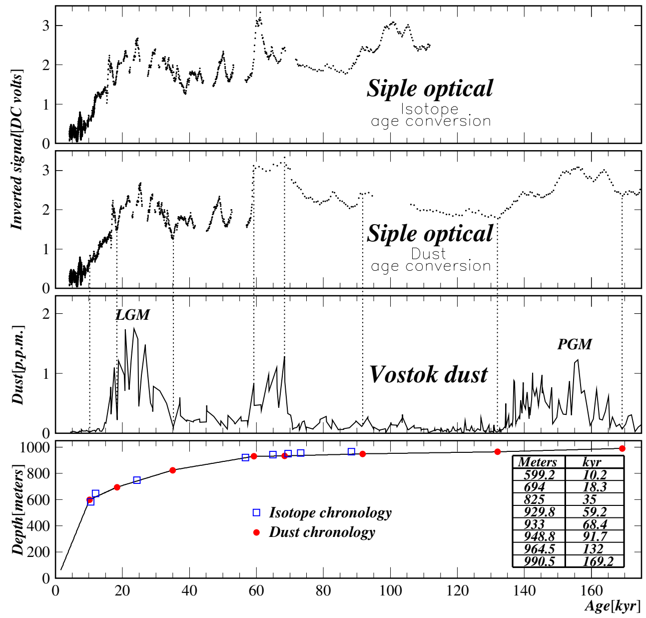

Figure 4. After removing the narrow spikes due to volcanic ash layers and inverting the ordinate, features in the optical data from Siple Dome (*top*) can be compared with climatic episodes at other locations by converting depth to age from stable isotope studies. The depth dependence of scattering from bubbles is manifest as an increasing baseline in the inverted signal. Because the prominent feature near bedrock at Siple Dome is not present in the dust record at Vostok during the same period, we speculatively associate it with the PGM in the Vostok core profile, and align prominent features in the two signals at several points to produce an alternate dust-band chronology (*bottom*).

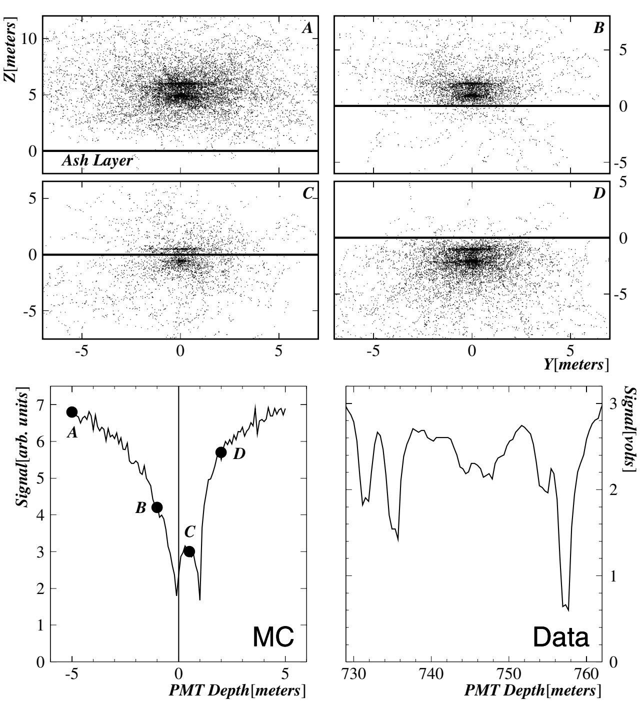

Figure 3. Monte Carlo simulation of the logger encountering a volcanic ash layer at $z = 0$. Frames A-D show the scattering points of all detected photons as the logger penetrates a highly absorbing 1 cm thick plane, with the same number of photons emitted in each frame. Most photons are confined within a few meters in the strongly scattering (bubbly) ice, and minima occur when the layer coincides both with the source and receiver. This simulated response reproduces the characteristic twin spike seen in the data at each ash layer.

Future development

We are developing and testing several improved versions of the logger with greater resolution and increased capability. The depth resolution of the logger is primarily determined by the degree to which the source is planar and thin. In Dust-logger-I, the LEDs have a wide emission angle, and the borehole was logged rather quickly (~20 cm s^{-1}). By us-

Table 1. Depths (D) of narrow bands due to volcanic ash, and their relative strengths (S, arbitrary units) estimated from the area under the curve.

D [m]	S [a.u.]	D [m]	S [a.u.]	D [m]	S [a.u.]
211	-	708	1	806	1
291	3	713	2	813	2
309	4	727	2	861	-
325	1	734	3	863	12
341	8	738	5	905	2
450	2	747	3	912	13
474	5	750	-	943	3
482	2	757	3	949	-
505	6	760	11	953	6
540	12	780	4	962	2
551	18	787	3	987	5
598	3	799	1		

ing a focused source and integrating signal over longer time periods, the logger resolution could be greatly enhanced. Monte Carlo simulation demonstrates that a Mark II design using highly collimated LEDs or a laser focused into a plane could easily resolve factor ~ 2 seasonal variations in dust concentration with a periodicity as small as a centimeter. This could make counting of annual layers dramatically easier, and might permit the testing of claims of modulated dust input on timescales from 11 to $\sim$2300 yrs.

The same general principles can be exploited, with modification, to construct instruments capable of detecting autofluorescence emission from biomolecules and possibly exotic microorganisms as a function of depth. A UV source excites compounds such as tryptophan, NADH and polyaromatic hydrocarbons. Their emissions can be detected either in a PMT masked by a dichroic mirror and narrow-bandpass interference filter centered on some longer wavelength, or collected into a spectrum analyzer (spectrometer, linear CCD array and CPU). Successful development of these loggers could lead to exploration of glacial ice at various latitudes, subglacial lakes such as Lake Vostok and, ultimately, the ice-covered Jovian moon Europa.

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R. Bay (bay@barney.physics.berkeley.edu), P. B. Price, Physics Dept., Univ. of California, Berkeley, CA 94720

G. Clow, U.S. Geological Survey, Denver, CO 80225

A. J. Gow, USACE CRREL, Hanover, NH 03755

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