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Two-dimensional electrical stratigraphy of the Siple Dome (Antarctica) ice core

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ABSTRACT. A two-dimensional array of electrical conductivity measurements (ECM) has been used to image the acidity of the Siple Dome (Antarctica) ice core in a vertical plane. Annual layering and possible stratigraphic discontinuities are apparent. A brief disruption to the chemical stratigraphy is detected at 680 m. Below 800 m, weaker layering occurs and is interpreted as the result of post-depositional migration of chemical species. This technique provides a way to observe the horizontal continuity of chemical layers in an ice core and identify some types of flow irregularity.

1. INTRODUCTION

Ice cores contain a layered stratigraphic sequence of ice that can frequently be interpreted as a simple depositional history without discontinuities or exchange of material from one layer to another after the firn has metamorphosed to ice. Ice cores are commonly visually examined on a light table after a smooth flat surface is prepared that runs the length of a ~1 m core. Recently, optical methods have been developed that use digital imaging to enhance features that are difficult to detect visually, and to provide a permanent record of the optical characteristics of the core. Visual methods are well suited for observing dust bands, bubble shape, size and density, and crystal size. In some situations these observations are interpreted to identify annual layers in the core. In other situations annual layers are not preserved, but the visual observations are still useful for interpreting the stratigraphy of the core and its relevance to the interpretation of other records (Alley and others, 1995).

A major limitation of visual stratigraphy is that it detects only features with a visual expression in the core. This means that bubbles and dust at high concentrations have the dominant influence, and ice chemistry cannot be observed. In many situations, bubbles and dust provide sufficient information to allow useful interpretations to be made. However, in some situations visible features are not sufficient for accurate dating, and in no situations does visible examination provide a complete picture of the stratigraphy. For example, the bubbles may be so uniformly distributed that they do not provide useful delineation of layering, or post-depositional changes such as ice flow and crystal growth can influence the bubble and dust stratigraphy differently from the chemical stratigraphy. In deep Antarctic ice, low dust concentrations and an absence of bubbles result in no significant visual stratigraphy.

The aim for this work was to develop a method to observe the stratigraphy of ice cores that does not rely on optical features in the core. Such a method would provide a useful complement to visual observations.

2. METHODS

The electrical conductivity measurement (ECM; Hammer, 1983) is one of the simplest quantitative methods for examining ice cores. This technique measures the current flowing between two electrodes that are in contact with the ice and have a direct current potential difference of ~1000 V. The electrodes are moved along the long axis of the core in what corresponds to a vertical direction in the ice sheet, and the measurement is made as a function of depth along the core. The geometry of the electrodes, applied voltage, surface preparation methods and sampling rate vary between different measurement systems. The robustness of the method is shown by the strong agreement between data collected with independent systems despite these differences (Taylor and others, 1993).

Our system (Taylor and others, 1992) uses a 1000 V potential difference between two gold electrodes that are 1 cm apart and have an elliptical surface area of 4 mm^2. The electrodes are moved along the long axis of the core, with both electrodes at positions that correspond to the same depth in the ice sheet. The ice surface is prepared by first using a horizontal band-saw to cut a flat surface parallel to the core axis, and then smoothing it using a powered woodworking planer. This results in a glass-like surface with typical dimensions of 100 cm × 9 cm.

In an aqueous solution, all the ions are mobile and can conduct an electrical current. In ice the larger ions are held in place by the ice lattice or immobilized at grain boundaries, and the small H^+ ions are mobile (perhaps as H_3O^+). The H^+ ions are the primary conductors of the direct current used in the ECM, and the ECM is commonly thought of as an indication of the acidity of the ice (Moore and others, 1992). In practice, the ECM is frequently reported in units of microamps, which is only meaningful when compared to measurements made with instruments with the same voltage and electrode geometry and at the same ice temperature. An advantage of the ECM is that high-spatial-resolution measurements can be made rapidly. Commonly the ECMs are made

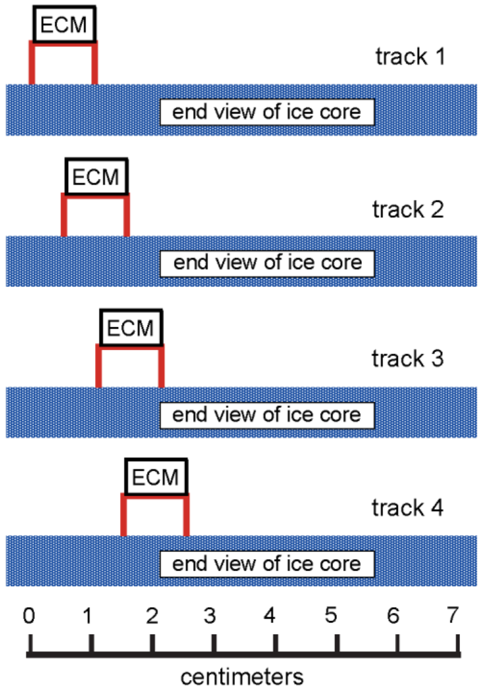

Fig. 1. Arrangement of electrodes on successive tracks. The blue boxes represent four views of the same 1 m section of ice core, which is viewed from the end looking parallel to the axis of the core. On the first measurement track, the two ECM electrodes (red lines) are placed near one edge of the flat surface that is parallel to the axis of the core. The ECM is measured as the electrodes are moved along the surface parallel to the axis of the core (i.e. towards the reader). On subsequent measurement tracks, the two electrodes are positioned 0.5 cm to the side of their positions on the previous track. There is a 50% overlap between the tracks. This process is repeated until the full width of the surface has been measured. Only four tracks are shown.

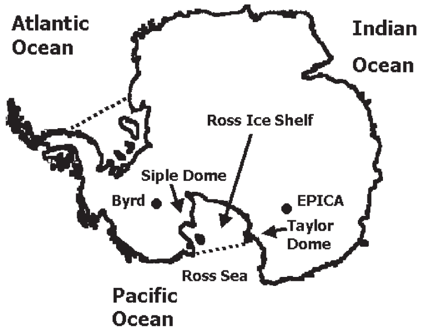

Fig. 2. Location map of Siple Dome. Siple Dome is located at 81.65° S, 148.81° W at an elevation of 621 m and has an ice thickness of 1004 m.

along 1 m of core in <1 min. The spatial resolution of the measurement depends on the electrode geometry, extent of the conducting pathway and sampling rate. Our system makes about 20 measurements each millimeter along the axis of the core, then averages and saves them as a single value every millimeter. The spatial resolution along the axis of the core (corresponding to the vertical direction in the ice sheet) is about 3 mm. (The divergence of the electrical field between the electrodes is about 3 mm along the axis of the core and is the factor with the greatest influence on the spatial resolution along the axis of the core. The 2 mm long electrode and 1 mm sampling rate do not limit the spatial resolution beyond the limitation associated with the spreading of the field lines between the electrodes.) The spatial resolution perpendicular to the axis of the core (corresponding to a horizontal plane in the ice sheet) is limited by the electrode separation of 10 mm. Each measurement value is representative of a flattened sphere in the ice sheet extending 3 mm vertically and 10 mm horizontally.

The ECM method is non-destructive and rapid enough for it to be practical to make measurements along many transects down a single 1 m long core. In the multi-track ECM method, adjacent transects are measured (Fig. 1) to build up a two-dimensional view of the electrical conductivity. This allows variations in the electrical conductivity of the ice to be determined along the axis of the core (corresponding to the vertical direction in the ice sheet) and perpendicular to the axis of the core (corresponding to a horizontal direction in the ice sheet.) In our system we offset the measurement transects by 5 mm, which is half the spatial resolution of the measurement in the horizontal direction.

Several groups have also made multi-track ECMs on ice cores. Zheng and others (1998) and Schwander (in Wolff and others, 1999) have made ECMs along multiple tracks and averaged them to reduce the influence of instrument noise and irregularities in the surface preparation. This results in a higher-quality one-dimensional measurement than when only a single track is measured. The amount of improvement obtained by averaging multiple tracks is dependent on the number of tracks, the level of electrical noise for the particular instrument and the quality of the surface preparation. Our system uses mechanical equipment to move the electrodes and prepare the ice surface, thus minimizing the influence of the operator. Repeated measurements along a freshly prepared single track show that measurements on a single track typically have a signal-to-noise ratio of more than 30 : 1, except when there is an error caused by a mechanical fault. Mechanical faults can be caused by nicks on the planer blades or electrodes, a defect on the ice surface caused by a millimeter-scale burst of the ice surface, contamination by the operator or ice build-up under the electrodes. Bad measurements caused by a mechanical fault can be difficult to identify when only a single-track measurement is made; however, when a multi-track measurement is made, the erroneous measurement is obvious. Although mechanical faults are uncommon, they occur often enough for the additional effort required for multi-track measurements to identify them to be recommended. Averaging multiple tracks also reduces variability in the signal caused by naturally occurring millimeter-scale variability in the horizontal direction. This naturally occurring small-scale horizontal variability has an undesirable influence when the data are used to identify annual layers. However the small-scale horizontal variability can also contain important stratigraphic information such as how consistent the layer is.

3. RESULTS

A 1004 m ice core was collected from Siple Dome, Antarctica (Fig. 2). Siple Dome is well situated both climatologically and glaciologically to preserve a climate record for the last ∼100 000 years. The current annual accumulation rate is 11.7 cm a^{-1} of ice, and the average surface temperature is −24.5°C. The multi-track ECM method was used to observe the stratigraphy over ∼0.5 m intervals at 30 depths. The depths were selected to sample both representative

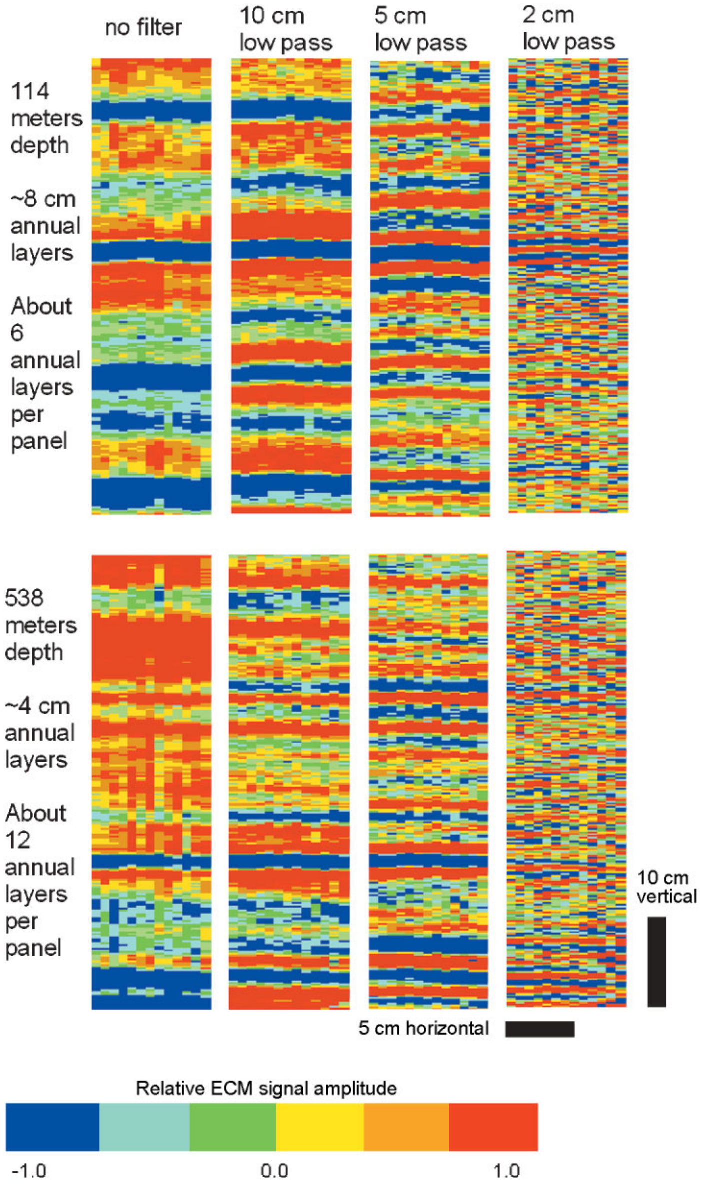

Fig. 3. Effect of filtering on multi-track ECM images. Each panel is an image of the ECM in a vertical plane near the center of the core. The top of the panel is up. Areas in red, green and blue have high, medium and low ECM values respectively. The ECM value that corresponds to each color is different in each panel so that the full range of colors is shown in each panel. Each image is made up of 14 parallel ECM transects that run parallel to the axis of the core. Each image is 50 cm high and 7.5 cm wide with a horizontal exaggeration of 2×. The images are from different depths and have been filtered differently, as explained in the text and labeled on the figure.

sections and sections of special interest. Poor core quality greatly constrained where measurements could be made because in many depth intervals it was not possible to locate an unfractured section of core of useful size.

The multi-track ECM data are displayed on a color-modulated cross-section that corresponds to a vertical plane through the core (Fig. 3). Red, green and blue areas represent high, medium and low ECM values respectively, corresponding to high, medium and low levels of acidity. The range of ECM values corresponding to each color is different in each cross-section so that the full range of colors is used in each cross-section. If this were not done, there would not be enough color range to show the stratigraphic detail in each cross-section.

The ECM is influenced by multi-year, annual and sub-annual variations. In Figure 3, multi-track cross-sections are shown for depths of 114 and 538 m. The annual-layer thicknesses at these depths are ~8 and ~4 cm respectively. In the unfiltered cross-sections the multi-year variations have the largest amplitude and prevent the smaller annual variations from being observed in the limited dynamic range of the color-modulated display, although the annual variations are evident in the full-range digital data. The multi-track ECM can be spatially filtered to attenuate variations in the vertical direction with a wavelength greater than a specified length. This high-pass filter does not attenuate variations in the horizontal direction. In this example a high-pass filter that removes variations with a wavelength of >10 cm in the vertical direction attenuates the multi-year variations and enhances the appearance of the annual layers at both depths. A high-pass filter that removes variations with a wavelength of >5 cm in the vertical direction attenuates the annual layers in the cross-section from 114 m where the annual layers are ~8 cm thick, while still maintaining the annual layers in the cross-section from 538 m where the annual layers are ~4 cm thick. A high-pass filter that removes variations with a wavelength of >2 cm in the vertical direction attenuates the annual layers in the cross-

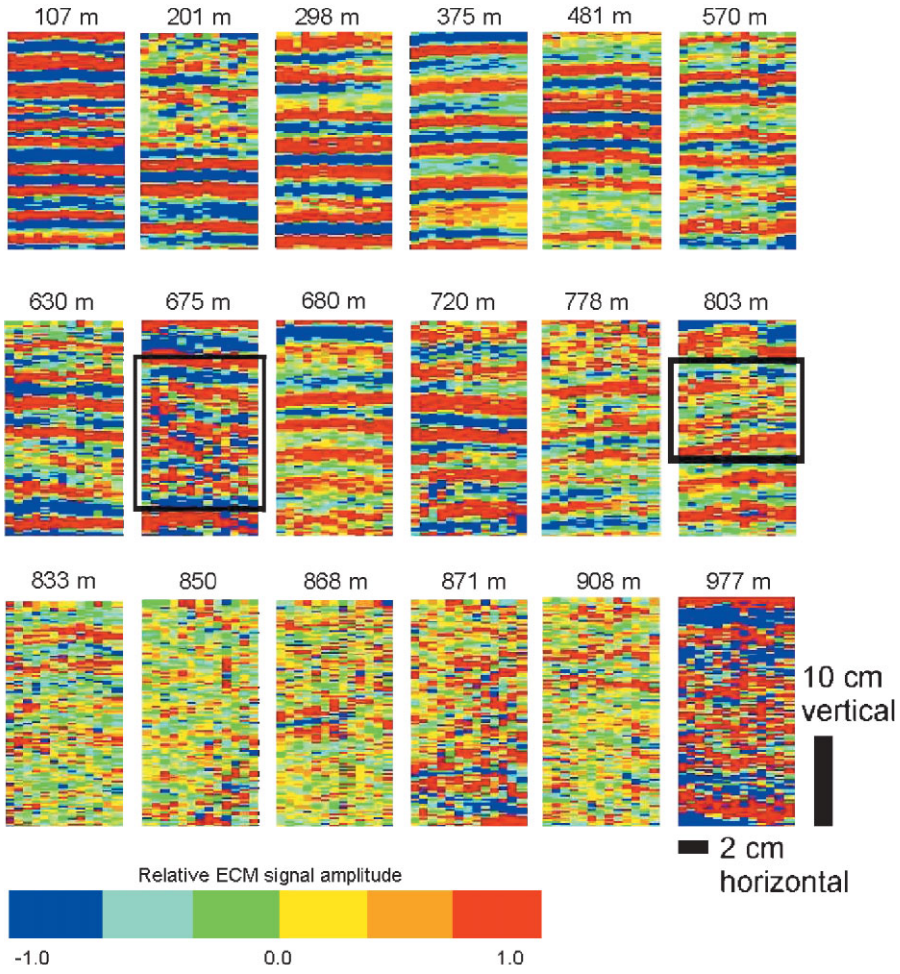

Fig. 4. Multi-track images from the Siple Dome core. These images have been filtered to remove vertical variations with a wavelength greater than 5 cm. The images are 25 cm high, 7.5 cm wide, with a horizontal exaggeration of 2×. The top depth of each image is indicated above it. The areas outlined with black boxes have irregular stratigraphy and are discussed in the text.

section from both depths and only preserves variations with a wavelength between 2.0 and 0.6 cm. Wavelengths below 0.6 cm are not recorded because they are above the Nyquist frequency of the instrument. There is not much signal in the 2–0.6 cm spectral band and hence the cross-sections only show remnants of the largest variations. Figure 4 shows the multi-track cross-sections for selected depths from the Siple Dome core. All the cross-sections have been filtered to remove variations in vertical direction with a wavelength of >5 cm, to emphasize the stratigraphy in the images

4. INTERPRETATION

The cross-sections in Figure 4 show well-defined and continuous layers down to 675 m depth (~15 000 years BP). At 675 m there is a 10 cm band of layers that are discontinuous, suggesting a stratigraphic disturbance that has disrupted the flat layering that occurs higher in the core. This could be caused by a low ice-accumulation rate, allowing large, steep sastrugi to form and then be buried, by diagenesis disrupting the layering, or other ice-flow distortions. The nitrogen-14 and argon-40 content of atmospheric gases trapped in the ice at 680 m indicates there was a time period when no gravitational fractionation of gases occurred in the firn (Severinghaus and others, 2003). The gas isotopes could be interpreted as an absence of the firn-layer or surface features that ventilated the firn such that fractionation did not occur. This is the only place in the core where the gas isotopes indicate that gravitational fractionation did not occur between the near surface and the bubble-trapping depth. The discontinuous layers in the multi-track image from 675 m may be evidence of fractures in the firn that prevented the normal fractionation of gas in the firn and led to the abnormal gas isotopes 5 m below. There may be other depth intervals within several meters of 680 m that have disturbed stratigraphy; however, multi-track measurements could only be made at 675 and 680 m because other unfractured sections of core suitable for multi-track measurements were not available.

The interval around 720 m (22 000 years BP) was investigated as frequently as ice quality permitted because this is where there is an abrupt shift in the δD_{ice} (Taylor and others, 2004). No evidence of abnormal stratigraphy was found; however, because poor core quality prevented continuous use of the multi-track ECM, this result cannot be used to conclude that irregular stratigraphy is absent near this depth. At 803 m depth (about 35 000 years BP) there are disturbed layers. It is not clear whether these are due to a structural phenomenon such as faulting or folding, an increase in surface roughness when this ice was deposited on the surface and then covered by snowfall, or post-depositional processes.

At 804 m and down to at least 908 m the layering is faint to non-existent. This corresponds to an interval where the ice crystals are very large; at below 833 m some crystals span the diameter of the core (personal communication from M. K. Spencer, 2003). Of many possible explanations for the loss of layering at this depth, perhaps the most direct is that many of the acidic impurities are associated with grain boundaries as films along two-grain boundaries or veins along three-grain boundaries (e.g. Wolff and others, 1988; Baker and Cullen, 2002; Rempel and others, 2002), and are moved with those boundaries during grain growth (Glen and others, 1975; Alley and others, 1986; Fisher, 1987; Barnes and others, 2003). Grains with diameters in excess of 10 cm imply boundary-migration distances of at least many centimeters. The multi-maximum c-axis fabrics observed in association with these layers are typically interpreted to indicate nucleation and growth of new, strain-free grains within strained ice lattices (e.g. Budd and Jacka, 1989; Alley, 1992). It is likely that ice with such large grains has been swept several times by moving grain boundaries. This repeated centimeter-scale movement of grain boundaries would disrupt layering of the acids that are located along grain boundaries. Chemical features with a spatial scale greater than the size of the crystals may still be preserved; however, it is possible that chemical reactions occurred when moving grain boundaries moved the chemical species.

At 997 m depth, just 7 m above the bed, there are well-defined layers. This depth is associated with basal ice that has a δD_{ice} value that is 85 per mil lower than ice immediately above it; the deeper ice has values more characteristic of ice-age conditions inland near Byrd Station (R. B. Alley and J.W. C. White, http://igloo.gsfc.nasa.gov/wais/abstracts00/Alley.htm). It is likely that there is a stratigraphic discontinuity separating this old ice of unknown origin from the ice above it, or that older through-flow of inland ice was interrupted when Siple Dome was isolated from the inland flow and assumed its modern configuration (R. B. Alley and J.W. C. White, http://igloo.gsfc.nasa.gov/wais/abstracts00/Alley.htm).

5. DISCUSSION

Displaying multi-track ECM as a cross-sectional image is a new way to view the stratigraphy of an ice core. Unlike visual stratigraphy, which is dominated by the optical appearance of dust and bubbles, multi-track ECM stratigraphy is dominated by the acidity of the ice. This makes electrical stratigraphy a good complement to optical and visual stratigraphy. The visualization technique also complements quantitative statistical analysis of multi-track measurements by providing an easy-to-comprehend image of the stratigraphy that reveals intricacies of the stratigraphy that are difficult to quantify. The technique reveals lateral continuity of layers, and any inclination of layers, which is not possible with traditional single-track ECM. The new method thus allows improved assessment of flow discontinuities and irregular impurity translocation, and should aid in annual-layer identification for dating. Our current system for making multi-track ECMs is somewhat awkward to use, and the poor quality of the Siple Dome core greatly limits the application of this method. Improvements that increase the measurement speed, and better core quality, will make it practical to use this method continuously along future ice cores. We expect this method to be particularly useful for deep Antarctic ice that does not have visible dust or bubbles. We hesitate to use data from a single core to investigate the many interrelated factors that influence the mobility of acids in ice. Multi-track measurements on ice cores with greatly varying rheology, impurities, temperature history and strain history would provide a dataset that could be used to formulate and test hypotheses about the movement of acidic species in natural ice.

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