Electrical conductivity measurements from the GISP2 and GRIP Greenland ice cores

K. C. Taylor*, C. U. Hammer†, R. B. Alley‡, H. B. Clausen†, D. Dahl-Jensen†, A. J. Gow§, N. S. Gundestrup†, J. Kipfstuhl‖, J. C. Moore¶ # & E. D. Waddington★

* Box 60220, Desert Research Institute, University of Nevada, Reno, Nevada 89506, USA
† Niels Bohr Institute of Astronomy, Physics and Geophysics, Department of Geophysics, University of Copenhagen, Haraldsgade 6, DK-2200 Copenhagen, Denmark
‡ Earth System Science Center and Department of Geosciences, The Pennsylvania State University, University Park, Pennsylvania 16802, USA
§ Cold Regions Research Lab, Hanover, New Hampshire 03755, USA
‖ Alfred Wegener Institut für Polar und Meeresforschung, Columbusstrasse, D-27568 Brenerhaven, Germany
¶ Arctic Centre, Box 122, University of Lapland, Rovaniemi SF96101, Finland
# British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 OET, UK
★ Geophysics Program AK-50 University of Washington, Seattle, Washington 98195, USA

THE direct-current electrical conductivity of glacial ice depends on its acidity[1–3], and can also indicate changes in climate, as ice formed in cold, dusty periods has a high concentration of alkaline dust[1,4,5], which significantly reduces the conductivity[6,7] compared to warmer, less dusty periods. Here we present electrical conductivity records for the Greenland Ice Sheet Project 2 (GISP2) and Greenland Ice-core Project (GRIP) ice cores, drilled 28 km apart to enable direct comparison of the results. The upper parts of both records are consistent with previous evidence from other Greenland cores[4,8–12] for a stable Greenland climate during the Holocene, and a series of warm events punctuating the last glacial period. However, there is a significant discrepancy between the two records in the bottom 10% of the cores, calling into question recent reports of climate variability in the last interglacial[4,8] and the penultimate glaciation[8]. At this stage, it is too early to say what exactly is causing the discrepancy, although ice flow may have introduced some discontinuities into the records. Further work will be necessary to establish how much climatic information it will eventually be possible to extract from the lower parts of the two cores.

The electrical conductivity measurement (ECM) method involves making continuous, high-resolution measurements along the full length of the core. Although in principle other climate proxies, such as oxygen isotope ratio, can be measured in the ice at comparable resolution, this is too intensive to be practicable for the entire core. In addition to confirming the findings from other parameters, the ECM method is therefore useful for identifying regions of the core that should be investigated at high resolution using more labour-intensive parameters. As outlined above, during cold periods glacial ice tends to be dustier, and hence more alkaline than during warm periods. Although this means that the ECM signal is smaller for ice

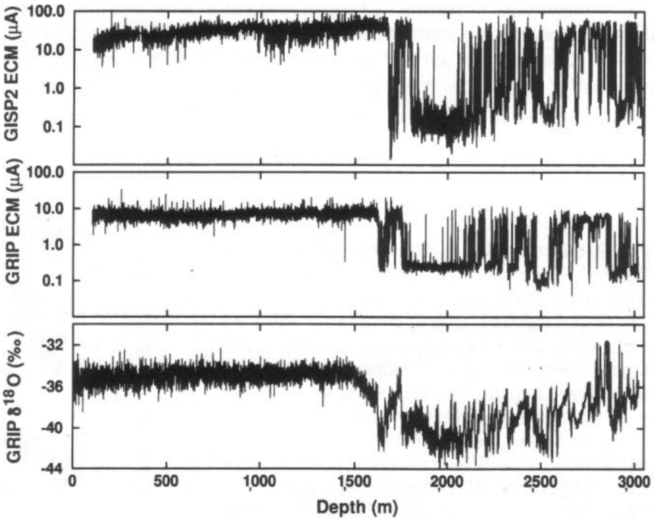

FIG. 1 Climate records from the Summit, Greenland ice cores. The ECM and GRIP δ^{18}O plots have resolutions of 10 and 55 cm respectively. The GISP2 ECM signal is the current flowing between two electrodes with a potential difference of 2,100 V; 1,250 V was used at GRIP. This difference does not affect the relative shape of the two ECM records. Volcanic eruptions, which are not visible in this plot because of the scale, will be discussed in a future paper.

deposited during cold periods, we have nevertheless managed to resolve considerable detail in the alkaline ice, including detecting the influence of dust layers that have been observed visually, and which may be annual[13,14]. Because the ECM response is non-linear and poorly calibrated between systems, the absolute value of the ECM is less significant than the pattern of relative amplitudes.

From the surface to a depth of 2,700 m at GISP2 (2,670 m at GRIP) the electrical conductivity measurement (ECM) records are well correlated, both for large trends that span hundreds of metres (Figs 1 and 2), and abrupt large-amplitude changes that span a few years or less (Fig. 3*a* and *b*). The excellent correlation of the ECM records in these parts of the cores give us great confidence in the completeness of the climate record above these depths. However, below the above-mentioned depth, the correlation between the ECM records is reduced (Fig. 4). Many layers <20 m thick do not correlate between the cores, and the interpretation of the record is less straightforward.

The dust layers that may be annual[13,14] appear as thin cloudy bands in most of both cores, especially in the sections that accumulated during cold periods. Continuous stratigraphic observations of the GISP2 core reveal that from the surface to 2,200 m depth the bands are undistorted. Below this, small-scale distortions in the record may be indication of larger-scale artefacts associated with ice flow. For example, sinuous wave-like distortions of the bands increase gradually with depth below 2,200 m. The shallowest overturned fold, with a vertical displacement of 1 cm, occurs at 2,400 m. Inclined layers that exceed the detection limit of 8° are first observed at 2,678 m. At GRIP, overturned folds were observed at 2,898 m and inclined layers (4° detection limit) were observed at 2,847 m. These features may also occur higher in the grip core, where stratigraphic observations are discontinuous. Folds that contain only a few dust layers may be associated with fold enhancement of annually varying depositional features such as sastrugi (wind induced ridges). In some cases the overturned folds contain many parallel dust layers, indicating that many years' accumulation has been folded and that depositional origins for the features are unlikely. In both cores layer inclinations of >20° were visible intermittently, some sections of which extended for several metres. The inclined layers and small overturned folds raise the possibility that larger folds or other structural features may exist in the lower portions of the ice sheet.

Two general categories of deformation mechanisms are possible; however we should stress that at present we lack any quantitative knowledge of their magnitude at the Summit sites. The first category results in differential thickness changes[12,15,16]. Soft layers may have been squeezed into a boudin structure characterized by being thicker, thinner, discontinuous, or a combination of these distortions at different locations. Hiatuses may exist in the stratigraphic record, but the stratigraphy is in chronological order. The second category of deformation mechanisms results in overturned folding[17] or intrusive flow[18], which alters the chronological sequence of the stratigraphy. These mechanisms can duplicate sections of the stratigraphy, so that ice that accumulated at a single time may appear in two or more non-adjoining segments of a core. Both categories of deformation have been extensively studied in geological environments[19,20] where multiple cores or outcrops make it possible to trace layers for extended distances. We should stress that much less is known about these mechanisms in ice sheets, where observations are more limited[21], although some observations have been reported[22,23]. Here we offer some speculation about the possible role that either of these mechanisms may have played at the GISP2 and GRIP drilling sites.

The two drill locations were chosen in different stress regimes to facilitate recognition of anticipated distortions due to ice flow[24,25]. The GISP2 site is located 28 km west of the present-day ice flow divide[26], and has a greater horizontal velocity than GRIP, which is on the present ice divide and dome. It is likely that this has been the situation for a few millions of years, but earlier divide migrations of a few tens of kilometres are likely to have occurred[24,25,27]. Because of the different locations with respect to the current flow divide, the ice under the sites is in different shear-stress regimes. The different shear-stress regimes will influence the type of deformation that is occurring at the two sites. In the pure-shear regime, associated with the vertical compression and thinning that is now under the ice flow divide at GRIP, boudins can occur. Overturned folds cannot be forming now[20], except for centimetre-scale drag features along the upper and lower margins of boudins, or near inclined bedrock. Boudins will alter the thickness of layers, possibly to the extent that some layers are reduced to a negligible thickness[15]. The chronological order of the layers will be preserved and features in the ice core are a record (although possibly incomplete) of climate events. In the simple shear regime associated with depth-dependent lateral extension (but no vertical thinning) that is currently occurring in the lower portion of the ice sheet under GISP2, overturned folding can occur[20]. This folding will alter the chronological order and introduce features into the ice-core record that are not related to climate. Ice that is folded out of chronological sequence may be physically mixed with adjacent ice during the

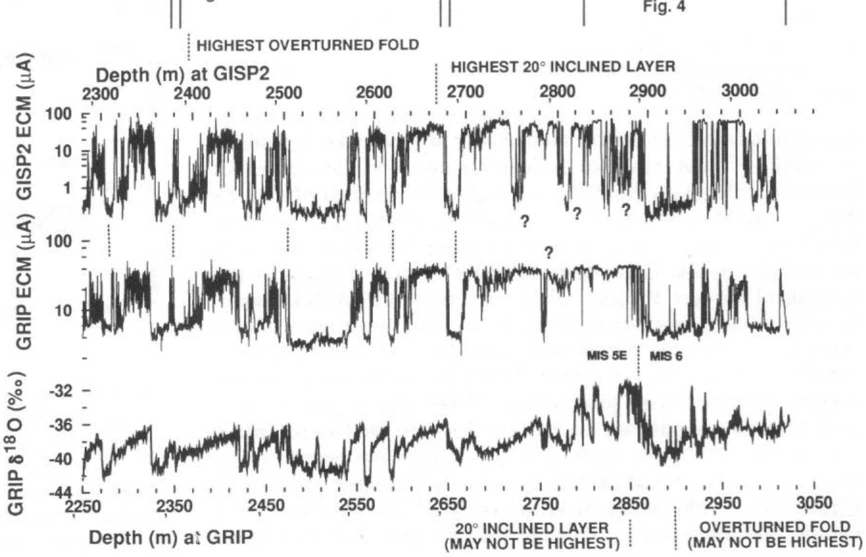

FIG. 2 Climate records from the bottom of the Summit, Greenland ice cores. The ECM and GRIP $\delta^{18}O$ plots have a resolution of 10 and 55 cm respectively. The GRIP and GISP2 ECM plots have been averaged over 10 cm. Some stratigraphic tie points between the ECM records are indicated by dashed lines. Features that do not correlate well are indicated by question marks. Low $\delta^{18}O$ values indicate colder periods. Low ECM values indicate alkaline ice, containing wind-transported carbonate dust. The identification of the marine isotope stage (MIS) 5e/6 contact in the GRIP core is from refs 4 and 8. (The parts of the record shown in expanded scale in Figs 3 and 4 are indicated at the top of the Figure).

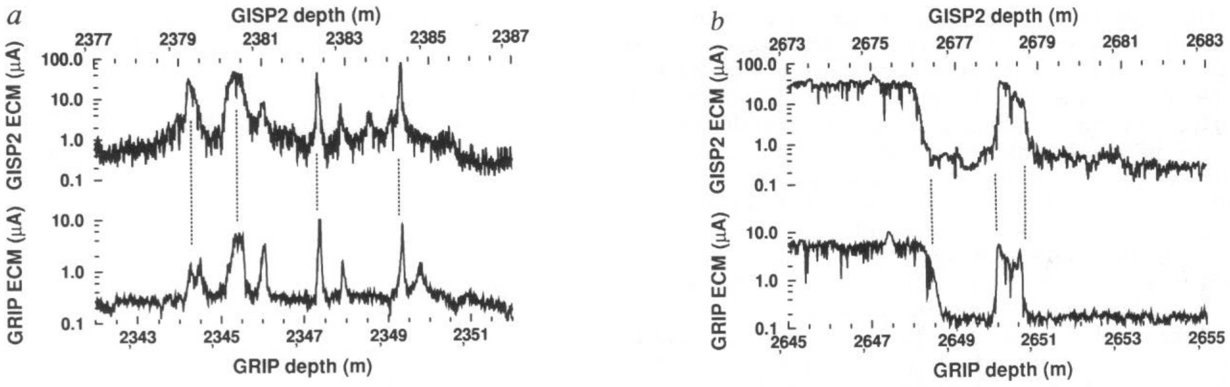

FIG. 3 ECM records of detailed features. The ECM plots have a resolution of 1 cm. Some stratigraphic correlations are indicated by dashed lines. Features thicker than 20 cm correlate between the cores. Poorly understood differences occasionally occur over intervals <20 cm; however, this occurs much less frequently and is on a scale an order of magnitude or more smaller than the differences that exist in the lowest 10% of the core. Features smaller than 10 cm may be independently influenced by localized variability in deposition and metamorphism.

folding process. If this occurred, the folded ice would no longer be a pure sample of the original unfolded ice.

Because the rate of deformation increases with depth, the most recent stress distribution will have had the greatest affect on the magnitude and distribution of deformation in the lowest portions of the ice sheet. Earlier divide migrations of tens of kilometres are likely[24,25,27], and would have had a weaker, but not negligible, influence on the deformation of the bottom 10% of the ice. Flow distortions caused by bedrock topography can also initiate overturned folding at off-divide sites regardless of the shear-stress regime. This begins at a distance above the bed that is comparable to the vertical relief of the bedrock topography[28], which is 200 m in the Summit region[29,30]. Folding can also be the result of migration of flow paths associated with changes in ice-sheet geometry[17].

These concepts of deformation mechanisms help us to interpret the stratigraphic differences between the two cores. It is difficult to correlate the 20-m-thick low-ECM layers (occurring in the GISP core around 2,755 m and 2,810 m) with corresponding features in the GRIP core. This could result from the formation of boudins at the GRIP site, which has greatly thinned these low-ECM layers. The formation of boudins is favoured in a pure-shear regime such as GRIP, where the thickness of layers is altered, as compared to the nearly simple-shear regime in the lower portion of the GISP2 core where layer thickness is largely preserved. In the GISP2 core, and to a lesser degree in the GRIP core, there are numerous thin low-ECM layers that occur just above the clean–dusty ice contact at 2,890 m at GISP2 (2,870 m and the marine isotope stage 5e/6 boundary[4,8] at GRIP). This is a likely place for the formation of folds, because of the differences in flow properties of ice with different impurity levels[15,31–34] and the high shear stress that occurs near the bottom[26]. It is possible that the low-ECM layers seen above this contact are artifacts of overturned folds which have moved dusty ice (low ECM) up and into clean ice (high ECM). Overturned folding occurs predominantly in a simple-shear environment and hence we expect it to be more abundant at GISP2. We note that more of these possible overturned folds of low-ECM ice are observed at GISP2 than at GRIP. Overturned folding may have occurred at GRIP under a previous flow regime associated with a different location of the ice divide[24,25,27], producing some of the variability in the GRIP record immediately above the contact at 2,870 m (GRIP depth).

We are confident of the climatic significance of long trends, including the sequence of interstadial events and the associated abrupt transitions, that are preserved above 2,700 m at GISP2 (2,670 m at GRIP). Below this, we speculate that the long low trend from 2,895 to 2,945 m at GISP2 correlates with 2,870–2,914 m at GRIP (marine isotope stage 6 (refs 4, 8)). With the data that are currently available below 2,700 m at GISP2

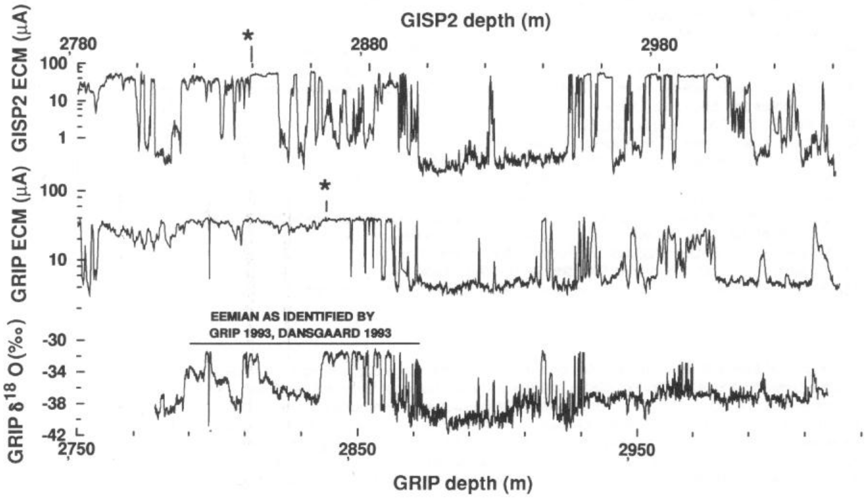

FIG. 4 Climate records from the bottom of the Summit, Greenland Ice cores. The ECM and GRIP δ^{18}O plots have a resolution of 10 and 55 cm respectively. There are many events <5 m thick that do not correlate between the cores. At these depths 5 m of ice contains the accumulation from several millions of years. Stars indicate where the character of the ECM signal changes. Above these transitions, the ECM records show a moderate level of variability when the ECM value is >10 μA. Below these transitions, the ECM records are remarkably uniform when the ECM value is >10 μA. The reduction in the variability of the ECM signal may be associated with centimetre-scale physical mixing during folding, or periods of exceptionally stable climate. The time period identified in refs 4 and 8 as the Eemian interglacial (marine isotope substage 5e) is shown for comparison.

(2,670 m at GRIP), it is not possible to determine the duration of anomalous features thinner than 20 m. In both cores, some of the features near the marine isotope stage 5e/6 boundary[4,8] that are thinner than 5 m may contain ice that is out of chronological sequence. These findings raise concerns about the interpretation of previously reported climate variations during the Eemian period (marine isotope sub-stage 5e, 2,790–2,870 m at GRIP)[4,8]. At present we are unable to say which, if either, core contains a more complete climate record.

Detailed consideration of the records may be able to determine the extent of deformation. For example, the several-century age difference (a few tenths of a metre at these depths) between the ice and the gas it contains[35,36] will result in abruptly changing chemical and gas features being preserved in ice that has different flow properties. Deviations from the anticipated offset between the records of ice chemistry and rapidly responding gases such as methane, may permit identification of features in the records that are introduced by ice flow. Detailed analysis of the crystal fabric, dust layers and chemistry may also be able to identify folded sequences. The upper 90% of the records are unaffected by ice flow and preserve a climate record with annual resolution. By detailed analysis of both cores, we anticipate that it will be possible to unravel many of the complexities that ice flow has introduced in the marine isotope stage 5e portion of the records. Deep Antarctic cores, where the marine isotope stage 5e portion occurs further from the bedrock, will also help resolve these issues. ☐

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