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Evidence for general instability of past climate from a 250-kyr ice-core record

W. Dansgaard*, S. J. Johnsen* †, H. B. Clausen*, D. Dahl-Jensen* N. S. Gundestrup*, C. U. Hammer*, C. S. Hvidberg*, J. P. Steffensen*, A. E. Sveinbjörnsdottir †, J. Jouzel ‡ & G. Bond §

* The Niels Bohr Institute, Department of Geophysics, University of Copenhagen, Haraldsgade 6, DK-2200 Copenhagen N, Denmark
† Science Institute, Department of Geophysics, University of Iceland, Dunhaga 3, IS-107, Reykjavik, Iceland
‡ Laboratoire de Modélisation du Climat et de l'Environment, CEA/DSM, CE Saclay 91191, and Laboratoire de Glaciologie et Géophysique de l'Environment, BP 96, 38402 St Martin d'Héres Cedex, France
§ Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York 10964, USA

RECENT results[1,2] from two ice cores drilled in central Greenland have revealed large, abrupt climate changes of at least regional extent during the late stages of the last glaciation, suggesting that climate in the North Atlantic region is able to reorganize itself rapidly, perhaps even within a few decades. Here we present a detailed stable-isotope record for the full length of the Greenland Ice-core Project Summit ice core, extending over the past 250 kyr according to a calculated timescale. We find that climate instability was not confined to the last glaciation, but appears also to have been marked during the last interglacial (as explored more fully in a companion paper[3]) and during the previous Saale–Holstein glacial cycle. This is in contrast with the extreme stability of the Holocene, suggesting that recent climate stability may be the exception rather than the rule. The last interglacial seems to have lasted longer than is implied by the deep-sea SPECMAP record[4], in agreement with other land-based observations[5,6]. We suggest that climate instability in the early part of the last interglacial may have delayed the melting of the Saalean ice sheets in America and Eurasia, perhaps accounting for this discrepancy.

In 1990–92, the joint European Greenland Ice-core Project (GRIP) drilled an ice core to near the bedrock at the very top of the Greenland ice sheet (72.58° N, 37.64° W; 3,238 m above sea level[7]; annual mean air temperature −32 °C). The 3,028.8-m-long core was recovered by an electromechanical drill, ISTUK[8]. Less than 1 m of core in total was lost in the drilling process. The deepest 6 m is composed of silty ice with pebbles. The core quality is excellent, except for a 'brittle zone' in the depth interval between 800 and 1,300 m.

Here we discuss a timescale for the entire core and present a continuous profile of $\delta^{18}O$ (hereafter denoted by δ, the relative deviation of the $^{18}O/^{16}O$ ratio in a sample from that in standard mean ocean water). In polar glacier ice, δ is mainly determined by its temperature of formation[9]. Profiles of several climate-related parameters spanning the last interglacial period (known as the Eemian period, or Eem) are being investigated by GRIP participants[3].

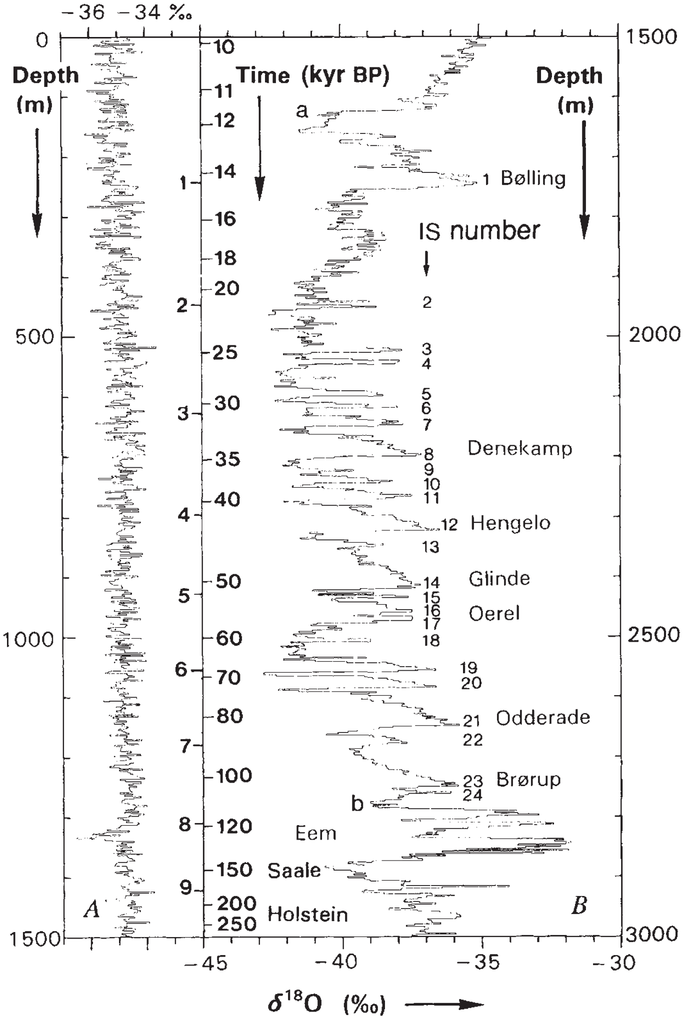

FIG. 1 The continuous GRIP Summit $\delta^{18}O$ record plotted in two sections on a linear depth scale: *A*, from surface to 1,500 m; *B*, from 1,500 to 3,000 m depth. Each point represents 2.2 m of core increment. Glacial interstadials are numbered to the right of the *B* curve. The timescale in the middle is obtained by counting annual layers back to 14.5 kyr BP, and beyond that by ice flow modelling. The glacial insterstadials of longest duration are reconciled with European pollen horizons[16].

The timescale back to 14.5 kyr BP (thousands of years before present) is derived by counting annual layers downward from the surface[1]. Beyond 14.5 kyr BP a timescale is calculated as

$$t = \int_0^z \mathrm{d}z/\lambda_z$$

t being the age of the ice and λ_z the annual layer thickness at depth z. A steady-state ice flow model[10] is modified by introducing a sliding layer at bedrock[11], and using a δ-dependent accumulation rate (λ_H) derived from all available λ_z data,

$$\lambda_H = \lambda_{H0} \exp\,[0.144\,(\delta + 34.8)] \text{ m of ice equivalent per year,}$$

λ_{H0} being the present value, 0.23 m yr^{-1} (ref. 1).

The other flow model parameters are as follows: The total thickness of the ice sheet H = 3,003.8 m of ice equivalent; the thickness of the intermediate shear layer h = 1,200 m; the ratio between the strain rates at the top of the silty ice and at the surface, f_b = 0,15; and the thickness of the silty ice layer, dh = 6 m. The latter value may be too low, but higher values would significantly influence only the calculated ages of the deepest 50 m (ice older than 250 kyr) which will not be discussed here.

The h and f_b values are chosen so as to assign well-established ages to two characteristic features in the δ record: 11.5 kyr for the end of the Younger Dryas event[1,12] and 110 kyr for the marine isotope stage (MIS) 5d[4], which appear at depths of 1,624 m and 2,788 m, respectively, in the δ record. These are points a and b in Fig. 1*B*. Back to 35 kyr BP the calculated timescale agrees essentially with that presented in ref. 1.

One of the assumptions behind the timescale calculation is that the stratigraphy has remained undisturbed, so that all annual layers are represented in a continuous sequence and thinned according to the depth-dependent vertical strain described by the flow model. This may fail at great depths if there is folding close to a hilly bedrock, and/or random thinning of layers of different rigidity (boudinage effect[13]).

Large-scale folding caused by bedrock obstacles hardly exists in the Summit area, however, because the bedrock is gently sloping (≤ 40 m per km) in a large area around the drill site[14]. Furthermore, according to radio-echo sounding records (L. Hempel, personal communication) the shape of internal reflection layers suggests that the long-term position of the ice divide was only 5 km west of the present Summit. Consequently, the ice movement at Summit has been essentially vertical in the past, confirming that the ice cannot have travelled long distances over hilly bedrock. Nonetheless, at great depths the boudinage effect may have caused small-scale disturbances. Some layers may have thickened at the expense of others now missing in the core. If so, the layer sequence may not be strictly continuous, but even then the broad outline of the timescale may still be valid.

Visible cloudy bands, probably indicative of former surfaces[15], lie almost perpendicular to the core axis down to ~ 2,900 m depth, corresponding to 160 kyr BP. Then follows a 54-m increment of apparently disturbed stratigraphy (S. Kipfstuhl, personal communication), possibly caused by the boudinage effect. Finally, the regular layer sequence is re-established from 2,954 m (210 kyr BP), but special caution should be applied beyond 160 kyr BP. The American GISP2 deep ice core being drilled 30 km west of Summit[2], may provide verification of the timescale.

A continuous δ record along the upper 3,000 m of the GRIP core is plotted on a linear depth scale in two sections of Fig. 1. The upper half of the record (Fig. 1*A*, δ scale on top) spans nearly the past 10 kyr, and each δ value represents the snow deposition through a few years near surface, increasing to 20 years at 10 kyr BP. Apart from the δ minimum at 8,210 ± 30 yr BP[1], the record indicates a remarkably stable climate during the past 10 kyr.

In the contrast, the rest of the record shown in Fig. 1*B* is dominated by large and abrupt δ shifts. Because of plastic thinning of the layers as they approach the bedrock, these 1,500 m of ice represent a much longer period of time than the 1,500 m above. On the right side of the record is an extension of the numbering of glacial interstadials (IS) introduced previously[1]. Furthermore, a series of European pollen horizons[16] (^{14}C dated back to 60 kyr BP) is reconciled with the longest lasting δ-based interstadials. The ^{14}C datings are all in essential agreement with our timescale once recent corrections to the ^{14}C scale[12] have been considered.

Figure 2 is a composite of five different chronological records. Figure 2*D* shows the upper 2,982 m of the Summit δ record plotted on the linear timescale in 200 yr increments. The vertical line is drawn for comparison with the Holocene mean δ value, −35‰. On the right-hand side of this line is a division of the last glacial cycles in European terminology. The adopted timescale is further supported, first by the numerous common features (particularly during the last glaciation) between the smoothed version and the other four records in Fig. 2 (exemplified by

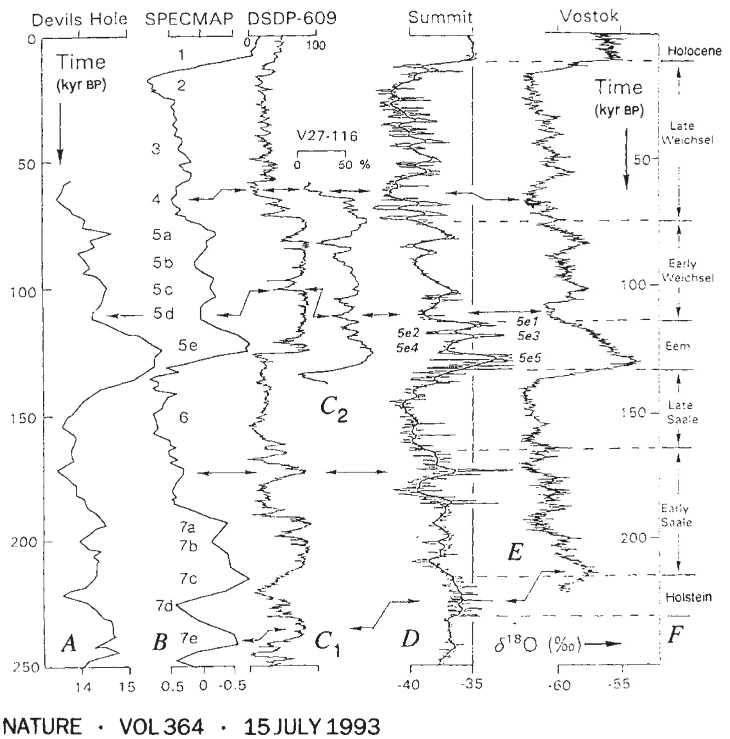

FIG. 2 Four climate records spanning the last glacial cycles and plotted on a common linear timescale. *A*, δ^{18}O variations in vein calcite from Devils Hole, Nevada[6]. Dating by U/Th. *B*, The SPECMAP standard isotope curve[4] with conventional marine isotope stages and sub-stages. Dating by orbital tuning. *C*, part 1. Grey-scale measurements along 14.3 m of ocean sediment cores DSDP site 609. Part 2, Per cent $CaCO_3$ in V27-116 (through stage 5) from locations west-southwest and west of Ireland. Scale in arbitrary units on top[24]. Dating by orbital tuning. *D*, δ^{18}O record along the upper 2,982 m of the GRIP Summit ice core. Each point represents a 200-yr mean value. The heavy curve is smoothed by a 5-kyr gaussian low-pass filter. Dating by counting annual layers back to 14.5 kyr BP, and beyond that by ice flow modelling. Along the vertical line, which indicates the Holocene mean δ value, is added an interpretation in European terminology. *E*, δD record from Vostok, East Antarctica[5], converted into a δ^{18}O record by the equation δD=8·δ^{18}O + 10‰. Dating by ice flow modelling.

dashed arrows); second, because a maximum entropy spectrum[17] comprising the total Summit record contains significant signals on the two Milankovitch cycles 41 kyr (obliquity) and, considerably weaker, 24/18 kyr (precession).

The violent δ shifts observed in Greenland cores are less pronounced in the δ record along the Vostok, East Antarctica, ice core[5] (Fig. 2*E*), probably because the shifts in Greenland are connected to rapid ocean/atmosphere circulation changes in the North Atlantic region[18,19]. Both records, as well as the δ record from Devils Hole[6] (Fig. 2*A*), and the records in Fig. 2*C* introduced below, imply MIS 5e (Eem) as an interglacial of considerably longer duration than estimated from sea sediment δ records, such as the SPECMAP record[4] in Fig. 2*B*. The disagreement may be explained, in part, by the climate instability recorded (Fig. 2*D*) in the early stages of Eem, which must have slowed the melting of the Saalean ice sheets in America and Eurasia. Further evidence of delayed sea level rise is found in records of the isotopic composition of atmospheric oxygen in the Vostock core[5]. If MIS 5e is defined as the period between the first and last years of higher than Holocene δ, it lasted nearly 20 kyr, from 133 to 114 kyr BP, according to the Summit record.

In Fig. 2*D* (and in other Summit records[3]), 5e stands out as an interglacial abruptly interrupted several times by periods as cool as 5a and 5c. A similar episode in 5e was previously demonstrated in the Camp Century and Devon Island ice cores[20,21], and given the new timescale, it could well be identical with one of the 5e cool spells indicated in Fig. 2*D*. The duration of 5e2 and 5e4 was apparently 2 and 6 kyr, and they define a tripartition of 5e. Carbon dioxide analyses along the Vostok ice core also suggest a partition of 5e[22], but Fig. 2*D* differs remarkably from most pollen and deep sea records, which show the Eem as a generally warm and stable period (see for example, ref. 16 and Fig. 2*B*).

The apparent disagreement may not be serious. Substantial global climate changes are generally more pronounced at higher latitudes. The cooling in western Europe corresponding to the long-lasting δ minimum 5e4 in Fig. 2*D* may therefore not have been deep enough to cause any marked change in the vegetation, and thereby in the pollen records. Sea sediment δ records are primarily indicative of the continental ice volume, which does not necessarily vary with temperature during times of no ice in North America and Eurasia. Furthermore, the resolution is limited by bioturbation and coarse sampling. Significant fluctuations of 5e have been recorded, however, in North Atlantic areas of high sedimentation rate ($\geqslant$5 cm kyr^{-1}), for example in core V28-56 from the Norwegian sea[23], and as colour and $CaCO_3$ concentration changes in central North Atlantic sediment cores[24].

The colour record from Deep Sea Drilling Project site 609 is plotted in Fig. 2*C*, part 1, on a timescale tuned[25] to orbital variations. This record has a resolution comparable to that of Fig. 2*D*. Disregarding MIS 2 and 3, where detrital grains of carbonate corrupt the grey scale, nearly all of the δ shifts can be recognized in the colour record, including some of the δ shifts in 5e. The colour scale reaches 'saturation' (note that 5a, and 5c and the warm phases of 5e appear equally dark), which may be why only one of the cool stages in 5e looks significantly different in colour. Several fluctuations in 5e are registered in cores recovered farther north[24]; for example see the inset of per cent $CaCO_3$ (indicative of biological activity) through MIS 5 from V27-116 in Fig. 2*C*, part 2.

The glacial cycles spanned by the Summit ice core appear different in Fig. 2*D*. For example, MIS 6 (late Saale) was apparently less cold and variable than late Weichsel, and a few spells of extreme warmth occurred in early Saale. Furthermore, the Holstein interglacial[26] (possibly MIS 7e) seems more stable than Eem, but less stable than Holocene.

In conclusion high resolution records suggest that, apart from the Holocene, instability has dominated the North Atlantic climate over the last 230,000 years. This applies to the Weichsel glaciation (MIS 2 to 5d), to the Eem interglacial (MIS 5e) whose progress was very different from the Holocene, the Saale glaciation (MIS 6 to 7d), and Holstein, the preceding interglacial (MIS 7e), according to the interpretation given in Fig. 2*D*. This emphasizes the question of whether the Holocene will remain stable in spite of the growing atmospheric pollution. □

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Decreased metal concentrations in ground water caused by controls of phosphate emissions

H. R. von Gunten* & Ch. Lienert

Laboratorium für Radiochemie, Universität Bern, CH-3000 Bern-9, Switzerland

A NEW generation of phosphate-eliminating sewage treatment plants and the recent prohibition of phosphates in detergents have considerably reduced the concentrations of phosphate in surface waters[1]. But there has been concern that replacing phosphate in detergents with complexing agents might cause increased mobilization of heavy metals, and consequent pollution of ground waters[2,3]. Here we present a twelve-year analysis of phosphate, manganese and cadmium in the river Glatt, Switzerland, and in an adjacent aquifer which is infiltrated by the river water. Together with a reduction of phosphate concentrations in both river and ground water over the study period, we find lower groundwater concentrations of manganese and cadmium. We postulate that lower phosphate levels have decreased the amount of oxidizable organic carbon in the river bed, and hence have

*Also at Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland.