velocity fault interiors), the seismological results are most simply explained by the absence of a wedge. Similarly, although the idea that deep earthquakes in detached slabs reflect metastability is attractive, calculations suggest that such metastability would not persist long enough (*10*), although it is not excluded given the poorly known age of slab detachment.

Given these difficulties, many participants concluded that the kinetics of the phase changes and slab thermal structure are sufficiently poorly known that although metastability is likely, it is not definitely required. As a result, two other possible mechanisms for deep earthquakes were explored. In one, deep earthquakes reflect a plastic instability where faulting occurs by means of rapid creep (*11*). In another, deep earthquakes occur by brittle fracture, which can occur at these high pressures because of the release of water from mineral structures (*12*). Although both these ideas have long histories, they are being revived because of the difficulties with the metastability model and because of new data on the rheology of slabs (*13*) and on the issue of whether water could be carried to great depth in mineral structures and released as the slab heats up (*2*). Neither model appears ideal: For example, the brittle fracture model does not directly address the observation that the depth range of deep earthquakes coincides with that of the olivine phase changes, and this process would be temperature controlled, giving rise to the same problems of fault dimensions that are too large as faced by the metastability model (*14*).

Although simple models based on idealized slabs explain some gross features of deep earthquakes, it appears that more sophisticated explanations must reflect the complex thermal structure, mineralogy, rheology, and geometry of real slabs. It seems likely that features of the simple models will need to be combined; for example, earthquakes may nucleate by one mechanism but propagate by a different type of shear instability. Although this situation is frustrating, it offers the exciting prospect of learning more about the complexities of real slabs from the details of deep earthquakes, in the same way that the occurrence of deep earthquakes provided the classic evidence for the very existence of subducting slabs.

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PERSPECTIVES: GEOSCIENCE

Calibrating the Isotopic Paleothermometer

Jean Jouzel

Paleoclimatologists who study the tiny air bubbles trapped in ice cores are very lucky. They can observe the composition of Earth's past atmosphere over hundreds of thousands of years and place greenhouse gas changes due to human activities in perspective (*1*). Now, two studies in this issue on pages 930 and 934 (*2, 3*) fully confirm that isotopic analysis ($^{15}N/^{14}N$ and $^{40}Ar/^{36}Ar$ ratios) can reveal the temperature shifts associated with abrupt climate changes. Even more important, this analysis provides precise information about the timing of these changes between high and low latitudes.

Glaciologists traditionally rely on the isotopic composition of ice to reconstruct continuous past temperature records. Fractionation produces a linear relation between annual oxygen-18 ($\delta^{18}O$) of mid- and high-latitude precipitation and mean annual temperature that is particularly well obeyed in Greenland and Antarctica. For example, $\delta^{18}O$ regularly decreases by 1 per mil every time the temperature drops by 1.5°C when going from coastal to Central Greenland (*4*). In using this relation as a paleothermometer, researchers have assumed that the present-day spatial relation does not change with time; that is, the spatial and temporal slopes are assumed to be similar. Simple models show that this assumption holds only if such factors as the evaporative origin and the seasonality of precipitation remain unchanged between different climates, which is not at all guaranteed.

These limitations have long been recognized and examined through simple and complex isotopic models (*5*). Central Greenland borehole temperature profiles effectively reveal that the Last Glacial Maximum (LGM) cooling at 20,000 years ago was about twice $\Delta T^{18}O$, the temperature changed predicted from the isotopic change on the basis of the spatial slope (*6*). Because of heat diffusion, however, this method cannot retain information about the numerous abrupt climatic changes documented in the isotopic record. The isotopic analysis of air bubbles can provide estimates of abrupt temperature changes on short time scales (a few decades or less) (see the figure).

Because of compaction, the density of snow increases with depth. Air is trapped when the firn (the consolidated snow) reaches a density of ~0.82 kg dm^{-3} and closes off bubbles of trapped gas. The entrapped air is thus younger than the ice matrix, with the age difference, Δ_{age}, depending on both accumulation and temperature (in Central Greenland, Δ_{age} varies between 200 and 900 years). Air composition is slightly modified by physical processes, such as gravitational and thermal fractionation. The latter depends on the thermal diffusion sensitivity and on the temperature difference between the surface and the close-off depth (*2*). Gases diffuse about 10 times as fast as heat, and in the case of a rapid change, this temperature difference is temporarily modified, which causes a detectable anomaly in the isotopic composition of nitrogen and argon. Both the depth of this anomaly, which allows estimate of Δ_{age} by comparison with the ice $\delta^{18}O$ record, and its strength provide estimates of rapid changes.

This approach was pioneered by Severinghaus, who first showed that thermal diffusion, a process familiar in the laboratory, can be observed in sand dunes (*7*). At the

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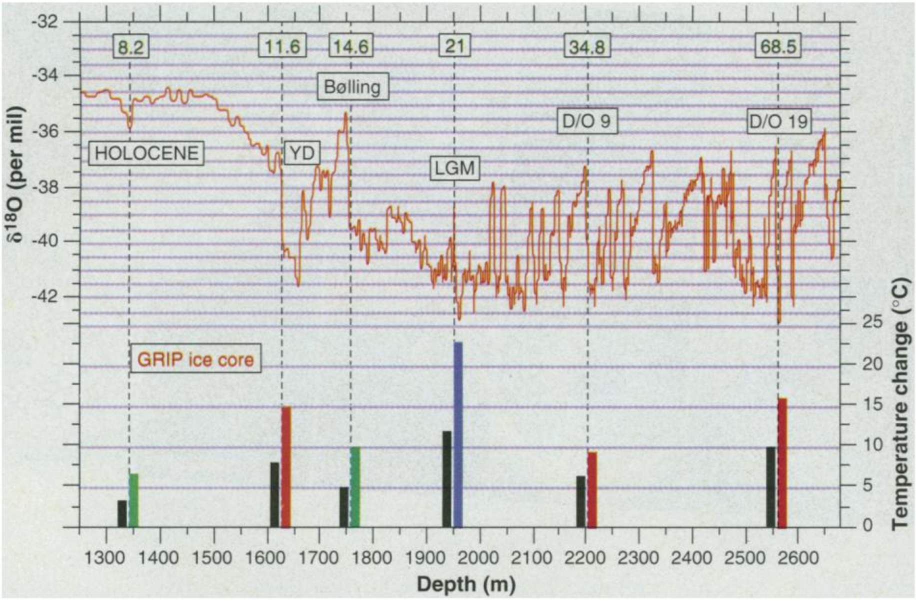
University of Rhode Island, he then demonstrated with Bender and other colleagues (*2*, *8*) that thermally driven isotopic anomalies are detectable in ice core air bubbles. Their landmark article published last year (*8*) focused on the rapid warming at the end of the Younger Dryas, 11,500 years ago. The inferred Δ_{age} value allows one to estimate that the Younger Dryas (YD) was 15° ± 3°C colder than today (see the figure), a value about twice that of $\Delta T^{18}O$ (*9*). In this issue, Severinghaus *et al.* (*2*) focus on the abrupt warming that terminated the glacial period 14,650 years ago and led to the Bølling transition. New determination of the thermal diffusion sensitivity and the combined use of nitrogen and argon isotopes permit separation of the thermal and gravitational effects. The warming, directly estimated from the size of the isotopic anomalies, amounts to ~10°C (see the figure), again about two times as large as $\Delta T^{18}O$.



Taking the climate's temperature. Absolute temperature change derived from the Greenland $\delta^{18}O$ record based on the present-day spatial slope of 0.67 per mil/°C (black bars), independent estimates from paleothermometry (blue bar), estimates of Δ_{age} (red bars), and the thermal isotopic anomaly (green bars). A 1 per mil $\delta^{18}O$ oceanic change has been accounted for when calculating the present-day–LGM temperature difference. The red curve corresponds to the Greenland Ice Core Project (GRIP) $\delta^{18}O$ record [average 100-year values reported on a linear depth scale; the GRIP and Greenland Ice Sheet Project 2 (GISP2) $\delta^{18}O$ records are similar when slight depth adjustments are accounted for]. (Dates in thousands of years ago are given in green numerals.)

Were the abrupt warmings that marked the start of the numerous Dansgaard-Oeschger (D/O) events that punctuated the last glacial period (*9*) also larger than initially thought? An answer is proposed by Lang and colleagues (*3*), from a detailed study of the $^{15}N/^{14}N$ anomaly associated with D/O 19, which occurred around 70,000 years ago (see the figure). These authors elegantly combine a depth-age model, which assumes that accumulation depends on temperature, and a firnification model to simulate this $^{15}N/^{14}N$ anomaly. The best fit with observations is obtained assuming an abrupt warming of 16°C, 60% higher than $\Delta T^{18}O$. This model estimate agrees with preliminary estimates proposed for D/O events between 40,000 and 20,000 years ago (*10*), but it would certainly gain by being confirmed by a precise evaluation of the thermal anomaly.

The figure summarizes how these various estimates compare with $\Delta T^{18}O$. It includes an additional result concerning the rapid cooling that occurred 8200 years ago (*11*). Temperature changes are consistently higher than $\Delta T^{18}O$, by a factor of about two for the LGM, for the Bølling and YD transitions and for the 8200 years before the present cooling and by about 50% for the D/O events investigated.

Recent LGM modeling experiments (*12*) strongly suggest that the factor of two difference was largely due to seasonal changes in precipitation. Such modeling experiments would also be extremely useful to assess the combined influence of changes in the origin (*3*, *5*, *12*) and the seasonality of the precipitation in the case of abrupt warming. Interestingly, those same LGM experiments (*13*) suggest that the temporal slope is closer to the spatial slope in Antarctica (less affected by seasonality) than in Greenland. This justifies the current use of the present-day spatial slope for interpreting Antarctic isotopic records. Thermal anomalies are probably too weak there (because of slower changes) to allow direct temperature estimates, but they should help constrain Δ_{age} and thus temperature changes. In short, there is still a lot to learn both in Greenland (in conducting a systematic study of D/O events) and Antarctica from the combined use of gas measurements and isotopic models to fully exploit the ice isotopic records that provide the only continuous, and now partially calibrated, ice core temperature reords.

Evaluating temperature changes associated with abrupt warmings is important but not critical for understanding the mechanisms involved (and those estimates only apply to Greenland). As amply discussed by Severinghaus and Brook (*2*), air bubble measurements offer much more. Rapid warming is generally characterized by an associated large and sudden methane concentration increase. The timing of methane increases with respect to the ice $\delta^{18}O$ record cannot be established accurately because of the uncertainty on Δ_{age} (~200 years). Instead, the timing with respect to the $^{15}N/^{14}N$ anomaly, also measured in the gas phase, is much more accurate. At the Bølling transition, atmospheric methane concentrations began their increase about 20 to 30 years after the onset of the abrupt Greenland warming (*2*). This finding constitutes a breakthrough which will be extremely useful for deciphering the mechanisms of abrupt climatic changes and already suggests a North Atlantic rather than a tropical trigger for the climate event (*2*).

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