lian cells. This process, which equalizes the expression of genes on the X chromosome in males and females, depends on the X-inactivation center (Xic) locus. This large (~500 kb), complex region templates the transcription of numerous noncoding RNAs that specify which X chromosome will remain active. All other X chromosomes in the cell are silenced through epigenetic modification. Selection of the active X involves transient association between Xic loci on different X chromosomes (*14*), and this homologous pairing requires transcription of at least two noncoding RNAs from the Xic locus, Tsix and Xite. However, it is unclear whether noncoding RNAs or simply the act of transcription is important for pairing (*15*).

Several features of RNA make it a good candidate for mediating homologous pairing. A nascent transcript anchored to a chromosome could emanate from the site of its transcription, providing a "feeler" to search for a homologous sequence. Some RNAs, such as ribosomal RNAs, are localized to discrete nuclear bodies, and recruitment of nascent transcripts could promote colocalization of the homologous loci. Although RNA-mediated pairing may not occur at all loci, a limited number of sites along a chromosome could serve as landmarks to establish a coarse alignment between homologs, which might subsequently be reinforced (or rejected) through recombination-based homology search or other processes. The mechanisms used by many eukaryotes to suppress the transcription of transposons and other high-copy DNA elements in germ cells could also serve to exclude these sequences from RNA-based homology search mechanisms.

Although it remains unclear how extensive a role is played by RNA in matching up homologous chromosomes during meiosis, even in *S. pombe*, the work by Ding *et al*. will motivate experiments in other model organisms. Identifying other components important for pairing at the *sme2* locus, such as protein factors that keep the nascent meiRNAs tethered in cis to their sites of transcription, and/or other loci that also pair robustly in the absence of recombination, will help to clarify the role of RNA in homologous recognition.

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CLIMATE CHANGE

The Ice Age Carbon Puzzle

A carbon isotope record helps to explain why carbon dioxide concentrations change during ice age cycles.

Edward Brook

Between about 24,000 years ago and today, the large ice sheets covering most of Canada and parts of Europe and Asia melted away, sea level rose by 120 m, Earth warmed by about 5°C, and rainfall and vegetation patterns shifted, sometimes abruptly. This dramatic natural climate experiment was set in motion by cyclic variations in the geometry of Earth's orbit, but a complex system of feedbacks governed the transition from a glacial to an interglacial state. One of the most important of these feedbacks was a well-documented change in the atmospheric greenhouse gas carbon dioxide (CO_2) (*1*). On page 711 of this issue, Schmitt *et al*. (*2*) provide important new carbon isotopic data that help to explain these changes.

Multiple studies of air trapped in polar ice have shown that ~17,500 years ago CO_2 levels started to rise from ice age levels of about 180 parts per million (ppm), reaching about 265 ppm 10,000 years ago (see the figure). Over the next 10,000 years, CO_2 slowly rose by another 20 ppm, until the rapid increase that started in the industrial age took over. Looking farther back in time, CO_2 variations appear to be a fundamental characteristic of ice age cycles (*3*).

Exactly why CO_2 changed like this has been vexing geochemists for decades. The carbon cycle involves uptake and release of CO_2 from both land and oceanic reservoirs, and these processes operate on many time scales. No one unified theory fits all available evidence, nor is the available evidence sufficient to test all hypotheses. The stable carbon isotopic composition of CO_2 could help to resolve these issues. This is because various carbon cycle processes fractionate the heavy isotope ^{13}C from the lighter ^{12}C. Photosynthesis, for example, preferentially removes ^{12}C from the atmosphere, and isotope fractionation during inorganic partitioning of CO_2 between the atmosphere and ocean is also important. However, apart from the clear isotopic signature of fossil fuel CO_2 input since the industrial revolution (*4*) and some hints from pioneering work (*5*, *6*), ice core isotopic measurements have not been detailed or precise enough to yield consistent patterns. Schmitt *et al*. now move the isotopic story forward with an important data set.

The primary problems to overcome have been technical. Available ice samples tend to be small, and the isotopic variations are also relatively small, making it both difficult and necessary to make precise measurements. Extracting air for CO_2 measurements requires either mechanical disaggregation or sublimation under vacuum, plus purification of CO_2, all of which can introduce artifacts. Furthermore, at deeper depths in the great ice sheets, air slowly changes from being occluded in bubbles to a solid hydrate form. Releasing air from hydrates by mechanical means is inefficient, and fractionation between bubbles and hydrates can cause further problems.

Schmitt *et al*. have overcome some of these challenges to produce the best record to date of the glacial to interglacial variations in stable carbon isotopes of CO_2. They adapted and painstakingly refined a traditionally cumbersome technique of sublimating ice and coupled it with a sensitive mass spectrometric technique to measure isotope ratios (*7*). Schmitt *et al*. augmented their latest sublimation data set with several others, although the results are primarily drawn from one Antarctic ice core. To create a unified picture of isotopic variations for the past 24,000 years,

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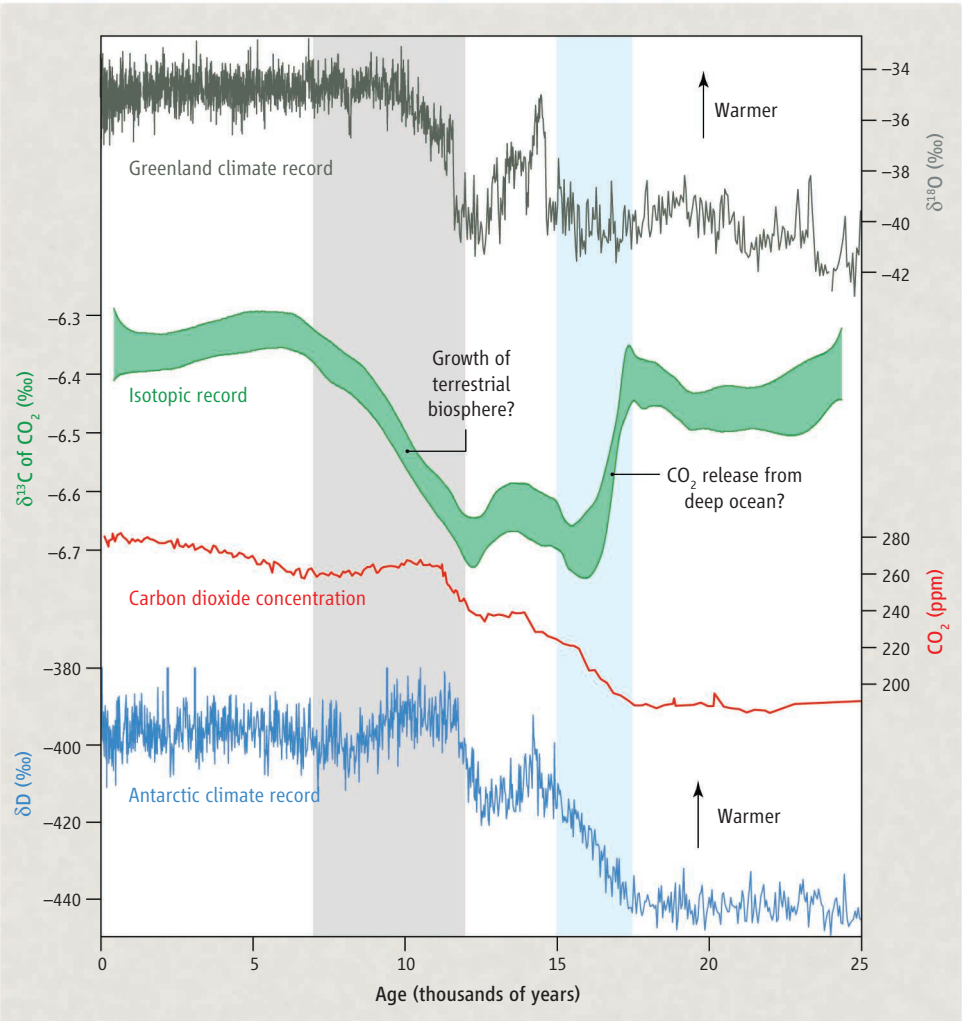

Glacial-interglacial change. Over the course of the past 24,000 years, CO_2 concentrations have risen (red curve) (*1*) as Earth emerged from glaciation, as shown by climate records from Greenland and Antarctica (gray and blue curves, respectively) (*14*, *15*). Schmitt *et al.* (*2*) report a record of the change in the $^{13}C/^{12}C$ ratio of CO_2 during this time (green curve). The isotopic ratio is expressed in delta notation, where $\delta^{13}C$ is the deviation of a sample ratio from that of an internationally expected standard, expressed in parts per thousand. Comparison of the CO_2 record with the isotopic record provides insights into the mechanisms behind the CO_2 rise. D, deuterium.

they smoothed the combined record using a method that incorporates analytical uncertainty. The resulting curve provides a good picture of isotopic variations on thousand-year time scales, at the expense of losing resolution of more detailed variations.

The data provide much food for thought. Going forward in time from 24,000 years ago, the isotopic pattern resembles a somewhat distorted letter W. The first event is a rapid 0.3 per mil depletion in ^{13}C between about 17,500 and 14,000 years, a time when the CO_2 concentration rose by about 60 ppm. Schmitt *et al.* suggest that this is consistent with release of CO_2 from a previously isolated deep-ocean reservoir that accumulated carbon as a result of oxidation of organic detritus sinking from the surface ocean. Variants of this hypothesis have been presented recently (*8*, *9*), and the idea gains support from the fact that the amount of radioactive ^{14}C in the atmosphere dropped drastically at about the same time as the carbon isotope ratio decreased (*10*). Studies of ^{14}C in fossil organisms found in deep sea sediments, which can provide estimates of the age of ancient deep ocean water, both support (*11*, *12*) and call into question (*13*) the existence and ventilation of the isolated reservoir.

The middle section of the W, between about 14,000 and 12,000 years ago, is subdued (see the figure). There are hints of variations that may be related to abrupt climate change seen in ice cores and other records, but they are too small to be interpreted clearly. This interval contains most of the remaining glacial-interglacial change in CO_2, and the lack of major isotopic change may indicate a different mechanism for this change than for the previous increase.

The other end of the W-shaped pattern is a slow rise in the isotope ratio between about 12,000 and 7000 years ago. Schmitt *et al.* suggest that this increase may reflect growth of the terrestrial biosphere, which preferentially removes ^{12}C from the atmosphere.

Schmitt *et al.* provide plausible interpretations of their results, but the role of other processes—including the input of magmatic CO_2 and the release of carbon from the terrestrial biosphere, among others—remains to be fully evaluated. Large-scale carbon cycle models will be needed to explore the full significance of these long-awaited data.

One limitation of the results is that the smoothed record does not allow us to see more rapid changes in the isotopic ratio of CO_2. Such changes are possible and could provide important clues to why so many of the inflection points during the glacial-interglacial CO_2 rise seem to correspond to abrupt shifts in climate seen in ice cores in Greenland and Antarctica (see the figure).

Schmitt *et al.* have paved the way for more laborious lab work that may further unwrap these and other mysteries, and may ultimately lead to a more complete understanding of carbon cycle feedbacks. Such feedbacks will operate during the current human experiment with the climate system, and therefore are important to understand.

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