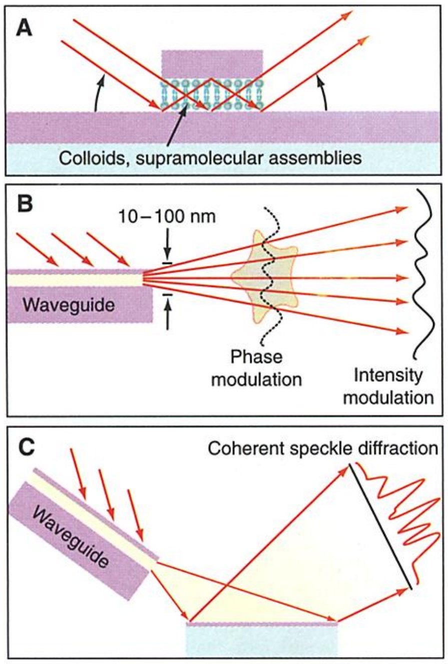

Waveguide applications. (A) Diffraction or spectroscopy of matter incorporated in the waveguide enhances the signal-to-noise ratio through resonance effects. **(B)** Waveguides can also serve as a point source of coherent x-rays. The intrinsic divergence can be used for coherent imaging or photon correlation spectroscopy in a projection setup, in which the information of a nanometer-sized object near the fiber tip is carried to a detector positioned in the far field. **(C)** In contrast to x-ray fiber optics, the beam is coherent; that is, the waveguide acts as a filter for the coherent fraction of the incoming beam, making it useful for photon correlation spectroscopy or coherent scattering.

nances can be excited in two-dimensional (2D) channel structures and clarify the corresponding coupling mechanism.

Many technological improvements will be required before their device can be used as an efficient x-ray point source. However, the reported ~2×10^4 photons per second out of a 33 nm by 68 nm opening is already impressive, representing a 70-fold improvement (gain) over a hypothetical pair of slits of the same dimensions under identical instrumental settings.

Given the rapid gain increases in planar waveguides in recent years, similar improvements in 2D waveguides through optimization of the fabrication process are likely. Relative to other focusing techniques, the 2D x-ray waveguide reported by Pfeiffer *et al.* offers unique opportunities for creating coherent hard x-ray beams with spot sizes below 100 nm.

Such beams could probe the structure and the dynamics of individual colloids, nanocrystals, supramolecular assemblies, or organelles in the cell. While structural information can be deduced from imaging or diffraction of the nanobeam, photon correlation spectroscopy may be used to study dynamics, even in the same experimental setup. In the latter case, the waveguide would replace the pinhole currently used in x-ray photon correlation experiments.

As an important step toward these goals, Pfeiffer *et al.* have performed an impressive demonstration of the basic resonance effect, which occurs when one shines a parallel synchrotron beam onto a suitably designed nanostructure. Almost any nanostructure can be analyzed by a diffraction experiment—but not every nanostructure can change the propagation of the beam.

Pfeiffer *et al.* have shown that the interaction of the beam with carefully designed interfaces goes beyond the well-known examples of other beam-shaping devices such as Fresnel zone plates, compound refraction lenses, and planar x-ray multilayers. Their work suggests that the combination of lithographic nanostructures and x-rays may have more surprises in store.

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PERSPECTIVES: PALEOCLIMATE

Earth's Long-Term Memory

Hugo Beltrami

For climate predictions from general circulation models to be interpreted with confidence, a robust record of past climatic changes is required. Without such a record, natural variability of the climate system cannot be separated from the possible changes induced by human activity. Resolving this issue is essential for addressing future climate change.

Two different approaches are widely used to reconstruct Northern Hemisphere climatic change during the last 500 to 1000 years. Both show a warming in the 20th century, but for earlier centuries they observe different patterns of climate change. Do these disagreements reflect only differences in the spatial distribution of sites, or are they due to intrinsic limitations of the methods?

The first method uses large data sets of various temperature proxies, such as tree rings and oxygen isotopes in ice cores, to construct a model of past temperature change (*1*). The second relies on geothermal data from boreholes worldwide to model ground temperature changes and the energy balance at Earth's continental surface (*2–4*).

Comparison of these multiproxy and geothermal paleoclimatic models is difficult because of differences in the spatial distribution of data. But preliminary comparison (*5*) yields some important differences. In particular, they disagree over the existence of a cold period between 1500 and 1800 A.D. Such a cold spell is documented in all geothermal models but does not appear as a strong signal in the multiproxy reconstructions (*1*).

To understand these discrepancies, we must first understand how surface temperatures are reconstructed in the borehole method and why direct comparison with multiproxy data is not possible.

If we assume that Earth's upper crust is in thermal equilibrium, then the temperature distribution in the upper few kilometers will be determined by the long-term (>1000 years) surface temperature and the internal heat flow (considered constant for time scales less than 10^6 years). Under the conditions of constant surface temperature and internal heat flow and homogeneous thermal properties of the underground rocks, the temperature increases linearly with depth. In most cases, the subsurface is not homogeneous, but thermal properties can be measured in rock samples and standard corrections applied.

The situation changes if Earth's surface warms (or cools). In this case, a quantity of heat will be gained (or lost) by the ground. These changes in the energy balance at the surface will propagate and be recorded underground as perturbations to the equilibrium thermal regime.

Typically, perturbations penetrate about 20 m in a year, 150 m in 100 years, and 500 m in a millennium, depending on the thermal properties of the subsurface rocks. Hence, recent energy balance changes at the surface remain recorded in the shallow subsurface. Analysis of these underground anomalies provides the basis of the borehole method. The temperature anomalies observed in the Northern Hemisphere (see the figure) show that the spatial variability of the surface energy balance is large.

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The ground temperature integrates the effects of energy exchange at the air-ground interface, continuously recording the energy balance at the surface. However, other surface factors—such as changes in vegetation cover, underground hydrology, topography variations, lateral heat conduction, and systematic variations of thermal conductivity of the subsurface rocks—can affect the underground thermal regime independently of climate. In fact, geothermal data have been used to determine the time of deforestation in areas of Canada (*6*). Therefore, borehole data must be screened carefully before they are analyzed for climate signatures.

Over the last decade, several groups have reconstructed ground surface temperature histories (GSTHs) from borehole temperatures (*7*). The energy balance at the surface of all the continents (except Antarctica) was estimated, allowing the total heat absorbed by Earth in the last 50 years to be calculated (*4*). Coupled with earlier work (*8*), this information clearly shows that all components of the climate system gained energy during this period, demonstrating the global nature of the present warming of our planet.

To assess the significance of past climatic changes inferred from geothermal data, we must explore the main strengths and limitations of the borehole method. Borehole temperature profiles are not a proxy for surface temperature, but rather a direct measure of the past temperature and energy balance at Earth's continental surface. The underground signal is, however, attenuated considerably through heat diffusion. This signal degradation imposes a physical limit on the information that can be retrieved from subsurface temperature anomalies. No mathematical trickery can overcome these limitations.

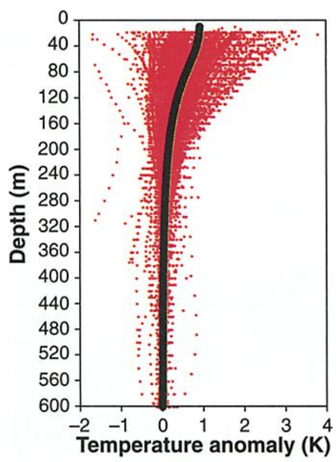
Data noise further decreases the resolution. As a result, the resolution of borehole data decreases with time. A climatic event affecting the ground surface can be resolved only if it persisted for ~60% of the time since its occurrence (*9*). An event that occurred 1000 years ago would therefore be detected as a single event only if it persisted for at least 600 years.

Because the borehole method uses simultaneous inversion (*10, 11*) to obtain site-, regional-, and large-scale averages, the maximum resolution for these ensemble averages is determined by the temperature log with the highest noise level—that is, the log with the lowest potential resolution. The current data set, derived from holes drilled for purposes other than climate reconstruction, represents a trade-off between resolution and spatial representation. Spatially homogeneous dedicated drilling and logging would alleviate this problem.

Because of the loss and variation of resolution through heat diffusion, borehole paleoclimatic reconstructions cannot be related directly to proxy or meteorological records, which contain information at higher and constant resolutions (*12, 13*). How, then, can we compare results from proxy and geothermal climatic reconstructions?

First, to bring the reconstructions to the same resolution, the high-resolution proxy reconstruction must be filtered in the same way as Earth filters surface temperature changes propagating into the ground. This can be accomplished by multiplying the proxy climatic reconstruction time series by the model resolution matrix from the inversion of geothermal data (*12*).

Second, keeping in mind that all paleoclimatic reconstructions are only models of past climatic variations and thus subject to corrections, we must clarify whether the multiproxy reconstruction (*1*) contains sufficient long-term information.



Borehole reconstruction of past temperatures. Red lines: subsurface temperature anomalies. Thick black line: average temperature anomaly. The vertical profile of the temperature anomaly depends on the history of energy balance at the surface. The area formed by the departure from the steady state (zero in the horizontal axis) from the surface to ~350 m provides a rough estimate of the total heat absorbed by the ground during the last 500 years. The anomalies indicate warming in most areas, but a few negative anomalies point to ground cooling in some areas (*19*).

The multiproxy method makes extensive use of tree-ring records, which require substantial preprocessing. A different and arbitrary age-related growth trend removal function is used to filter each tree-ring time series. As a result, trends of more than a few decades may be lost (*5, 14*). Furthermore, filtering takes place at different bandwidths for each tree. All processed dendrochronological time series are subsequently merged to form standardized chronologies. Spectral analysis of processed standardized chronologies is therefore uncertain for periods longer than a few decades.

This problem has recently been overcome by Esper *et al.* (*15, 16*), who reported a new method that preserves long-term trends in tree-ring data. This method must be applied to the tree-ring data used in constructing multiproxy models. The effects of age-related filtering on the long-term results could then be assessed. This reanalysis would not change the conclusions in (*1–4*) regarding the unprecedented character of the rate of change in temperature for the recent warming.

At the same time, regional comparisons of multiproxy and geothermal reconstructions should be carried out wherever allowed by the data. Large-scale averaging of GSTHs may have masked part of the cooling and recovery signal from the so-called Little Ice Age, perhaps because not all boreholes in the analysis have the same depth ranges (the deepest boreholes dominate the long-term GSTH).

For example, in some parts of Canada, evidence from geothermal data for the Little Ice Age is widespread, and in some areas individual GSTHs appear to be similar to the multiproxy reconstruction (*17*), including a cold period qualitatively similar to the Little Ice Age. However, in other parts of Canada, the Little Ice Age is not present in geothermal data (*18*). Examination of such small-scale discrepancies and similarities from proxy and borehole methods should provide insights into how robust the reconstruction methodologies are, and should help to discern the spatial variability of the Little Ice Age.

Clearer insights into past climatic changes should result from integrated analyses in which all models of paleoclimatic reconstruction are interpreted jointly to maximize their strengths and minimize their weaknesses. Interdisciplinary approaches and collaborations across fields are more important than ever in this endeavor.

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