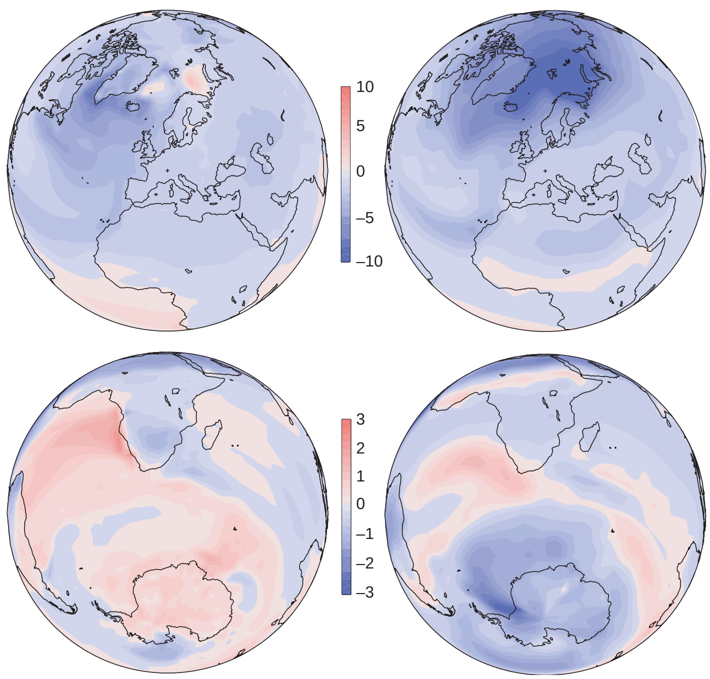
PERSPECTIVES: CLIMATE CHANGE

North-South Connections

Thomas F. Stocker

Between 18,000 and 10,000 years before the present (B.P.), the last ice age came to an end. During this time, a series of abrupt climate changes shook the Northern Hemisphere, with global repercussions (*1*). On page 1862 of this issue, Morgan *et al.* present data from a high-resolution ice core from Antarctica that put tighter time constraints on the sequences of climate changes in the Northern and the Southern Hemispheres (*2*).

Earlier studies found that during cold periods in Greenland, Antarctic warming trends occurred, and that their reversal coincided in turn with abrupt warmings in Greenland (*3*, *4*). Together with climate simulations, this observation led to the "bipolar seesaw" hypothesis of deglacial climate change (*5*, *6*). Climate simulations showed that the north-south coupling stemmed from changes in the thermohaline circulation (THC) of the Atlantic Ocean.



Shutting down the THC. Changes in Earth's surface temperature due to a collapse of the Atlantic THC, as simulated by two coupled atmosphere-ocean climate models (*9*, *10*). In both models, cooling is strongest in the North Atlantic and extends over much of the Northern Hemisphere (**top**). Predicted changes in the Southern Hemisphere (**bottom**), especially over Antarctica, are not yet consistent across different models. A sudden resumption of the THC would lead to the reverse response: a rapid warming in the north and some cooling in the South Atlantic and Indian oceans.

The new ice-core record from Law Dome, Antarctica, challenges this simple concept (*2*). At this near-coastal site facing the Indian Ocean, more snow is deposited per year than at any other deep ice-core location in Antarctica. This fast deposition has one important advantage: It makes it easier to date the ice.

Precise ice-core dating requires knowledge of the age not only of the ice itself, but also of air bubbles enclosed in it. Because the top layers of an ice sheet are highly porous, modern surface air diffuses down until it reaches the depth where it is enclosed. The age difference between enclosed gas and ice, Δage, can be as large as a few thousand years in Antarctic ice cores, seriously affecting the precision of a common time scale with other ice cores. Due to the high snow accumulation, Δage at Law Dome is only about 60 years, increasing to about 100 years at 10,000 years B.P. and 400 years at around 15,000 years B.P.

Morgan *et al.* use measurements of methane and oxygen-isotope composition in air bubbles of the ice core, along with a glacier flow model and a model that calculates Δage as a function of air temperature and accumulation rate, to synchronize their climate record with those from Greenland. In agreement with previous studies using Antarctic ice cores (*4*), they find that temperature at Law Dome increased steadily from 19,000 to 10,000 years B.P., but that this warming was interrupted by an 1800-year-long cooling trend, called the Antarctic Cold Reversal (ACR). The beginning of the ACR should—according to the bipolar seesaw hypothesis—coincide with the abrupt warming in Greenland at 14,500 years B.P. But Morgan *et al.* place the ACR at 15,000 years B.P., when it was still cold in Greenland. This finding is a serious challenge to the bipolar seesaw hypothesis.

A weakness of the hypothesis is the assumption that climatic changes in Antarctica are directly connected with those in the rest of the world. Such a direct connection is undisputed for time scales of many thousand years and longer. But it may not hold true for rapid changes on time scales of centuries or less, because both atmosphere and ocean maintain strong latitudinal temperature gradients across the polar vortex and the Antarctic Circumpolar Current, respectively, which influence the transfer of climate signals.

The limitations to our understanding of rapid climate change in Antarctica are illustrated by simulations with two different models (*7*, *8*) of the response of surface air temperature to a collapse of the THC (see the figure). Because the THC carries a substantial amount of heat northward in the Atlantic, its collapse triggers strong cooling in the North Atlantic region and the entire Northern Hemisphere (top panel). In most of the south Atlantic and the southern Indian Ocean, both models show warming of the ocean surface (bottom panel). But further south and in Antarctica, the models disagree: One predicts cooling over the Southern Ocean and Antarctica (*7*), whereas the other shows warming of almost the entire Southern Hemisphere (*8*).

If climate models do not yet deliver definitive answers regarding temperature changes in Antarctica associated with abrupt changes in the north, additional paleoclimatic data may advance our understanding. Measuring the two stable isotope ratios of the water molecule (^{2}H/^{1}H and ^{16}O/^{18}O) in polar ice cores yields information on surface temperature changes at the location from where the precipitation originates (*9*). With this method, Stenni *et al.* (*10*) found an Oceanic Cold Reversal (OCR) of less than 1°C in the Indian Ocean, about 800 years after the ACR (*11*). If the ACR started about 500 years earlier (*2*) than hitherto assumed, the OCR would come within 300 years of the abrupt warming in Greenland at around 14,500 years B.P. Given the uncertainties of Δage and the difficulty of placing the beginning of the OCR in a noisy record, synchroneity with the sudden warming in Greenland may be a possibility.

Such synchroneity would provide unexpected support for the hypothesis that the Atlantic THC plays a crucial role in deglacial climate change. Both climate models agree (see the figure) that the sea surface temperature change in the Indian Ocean is opposite to that in the North At-

The author is in the Climate and Environmental Physics Division, University of Bern, 3012 Bern, Switzerland. He is currently at Institut Pierre Simon Laplace/Laboratoire du Climat et de l'Environnement, 91198 Gif-sur-Yvette, France. E-mail: stocker@climate.unibe.ch

CREDIT: G. SCHMIDT/NASA-GISS AND M. VELLINGA/HADLEY CENTRE lantic—that is, a sudden warming in the North Atlantic would produce an OCR in the Indian Ocean. This finding (*2*) may solve the OCR problem, but leaves us in limbo regarding the origin of the ACR.

How robust are the findings of Morgan *et al.*? One limitation is that Δage reaches similar values at 15,000 years B.P. as in previous ice cores and that the uncertainties of the synchronization are thus not much reduced (*12*, *13*). The authors therefore present a second chronology for their ice core. With this alternative but less likely chronology, the beginning of ACR occurs at a similar time as in other Antarctic ice cores.

A second problem is not specific to this ice core. Maxima and changes of trends in high-resolution paleoclimatic records may result from natural variations that do not represent large-scale climate signals but are due to local processes. This limitation can only be reduced by additional high-resolution ice cores and a better understanding of local processes.

Further progress will come from new high-resolution Antarctic ice cores (*14*), particularly from locations where a higher fraction of precipitation originates from the Atlantic Ocean. In combination with the vast archive of marine sediment cores, the latter will provide a more spatially complete picture of abrupt climate changes and glacial-interglacial transitions. Recent paleoclimate records from the tropics show remarkable climate fluctuations during deglaciation (*15*), underscoring the necessity to integrate this region more completely into our thinking.

References and Notes

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6. This behavior is sometimes called "antiphasing" between north and south. The term "antiphasing" ignores, however, the fact that adjustment to thermal anomalies in the Southern Hemisphere evolves qualitatively differently from that in the north. Because of the large thermal heat capacity of the Southern Ocean, an abrupt cooling in the Northern Hemisphere due to a collapse ot the THC within less than a decade leads to a millennial warming trend in the south Atlantic.
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11. The deglacial OCR can also be detected in the deuterium excess records of other Antarctic ice cores (F. Vimeux, personal communication).
12. The identification of annual layers would be an independent constraint on the accumulation rate, but annual layer thickness is estimated to be less than 2 mm at 14,000 years B.P. Generally, at high concentrations, cosmogenic isotopes (^{10}Be, ^{36}Cl) carry a global signal. Used as a complementary method for synchronization, they circumvent the problem of Δage. ^{10}Be and ^{36}Cl concentrations were highest from 36,000 to 42,000 years B.P. It will be crucial to determine the north-south connections during this earlier time of abrupt climate changes.
13. G. M. Raisbeck, F. Yiou, J. Jouzel, *Geochim. Cosmochim. Acta* **66**, A623 (2002).
14. Deep ice-core drillings at Siple Dome (81.6°S, 148.8°W) by the United States, at Dome F (77.3°S, 39.7°E) by Japan, and at Kohnen Station (75°S, 0.07°E) as part of the European EPICA project.
15. A. Koutavas, J. Lynch-Stieglitz, T. M. Marchitto Jr., J. P. Sachs, *Science* **297**, 226 (2002).

16. This work is supported by the European Commission project POP. I thank G. Schmidt and M. Vellinga for providing data from their model runs; R. Pawlowicz for producing and sharing Matlab code for geophysical mapping; and T. Blunier, G. Delaygue, J. Jouzel, V. Masson, G. Raisbeck, J. Schwander, B. Stauffer, T. van Ommen, and F. Vimeux for valuable discussions.

PERSPECTIVES: GEOLOGY

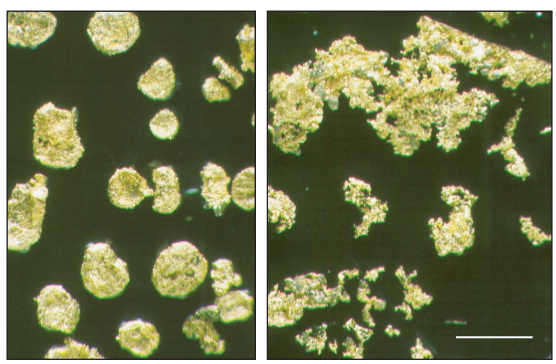
Genesis of the World's Largest Gold Deposits

Hartwig E. Frimmel

Almost 40% of all gold mined during recorded history has been recovered over the past 120 years from a single ore province: the Witwatersrand Basin in South Africa. Today, the gold-mining industry in the Witwatersrand has passed its maturity, but it is set to remain the world's leading gold producer. Estimated resources in the province still represent ~35% of world gold resources (*1*, *2*).

Despite its enormous economic significance and hundreds of research papers over the past decades, no consensus has been reached on the origin of the gold. A major breakthrough reported by Kirk *et al.* on page 1856 of this issue (*3*) should bring this debate to a close.

Two models have been suggested to explain the formation of the Witwatersrand gold deposits: a sedimentary placer model and a hydrothermal model. According to the former, the gold was introduced into its host rocks by mechanical erosion of gold-bearing hinterland and fluvial transport into a sedimentary basin. Further upgrading of the gold by sedimentary reworking and eolian deflation is indicated by the preferential occurrence of the gold in conglomerate beds above unconformity surfaces (shaped by weathering, erosion, or denudation) and its association with ventifacts (pebbles faceted by the abrasive effects of windblown sand) (*4*). This model finds support from a strong sedimentary control on ore grade, with the Witwatersrand gold being concentrated in the coarsest grained sediments of the succession.



Contrasting morphological types of gold. The gold particles shown here were released by digestion in hydrofluoric acid from a single hand specimen of Witwatersrand ore (*9*). **(Left)** Rounded, disk-shaped to toroidal, detrital particles. **(Right)** Hydrothermally mobilized, secondary gold. Scale bar, 0.2 mm.

When studied under a microscope, however, most of the gold appears to have crystallized after deposition of the host sediment. Furthermore, the Witwatersrand sediments show signs of having undergone significant metamorphism and hydrothermal alteration. These observations led to the competing hydrothermal models, in which the gold was introduced into the host sediments by hydrothermal or metamorphic fluids (*5*).

A major advance in constraining the age of sedimentation of the gold-bearing strata was recently reported by England *et al.*, who found that most of the gold occurs in sediments deposited between 2890 and 2760 million years ago (*6*). Kirk *et al.* now report Re-Os age data (*3*) that provide the first direct constraint on the age of the gold. The new data are in good agreement with previous attempts to date rounded pyrite and uraninite (*7*, *8*), which are closely associated with the gold. An age of around 3030 million years is now indicated not only for these other heavy minerals but also for the gold.

This is clearly older than the maximum age of sedimentation, and both the gold and the rounded pyrite must therefore have entered the host sediments as detrital particles. The microscopic observation of gold having formed relatively late in the crystallization history of the host rock is then best ex-

The author is in the Department of Geological Sciences, University of Cape Town, Rondebosch 7701, South Africa. E-mail: hef@geology.uct.ac.za