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Earth & Space

What causes an Ice Age to end?

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Ice-age cycles define the major climate features of Earth's geologically recent past. Combining information from caves, deep-ocean sediments, and astronomical calculations can help unravel when and why these cycles occur.

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Earth's climate over most of the last million years was much colder than the present. Massive ice sheets repeatedly covered large parts of North America and Eurasia. Periodically, these ice sheets melt when average global temperatures climb sharply to levels of today. Scientists have long suspected that these 'terminations' are triggered by changes in Earth's orbit, which govern the distribution of solar energy, or insolation, reaching the Earth's surface. But determining which orbital parameter is most important is elusive. The orbital parameters with the most significant influence on climate are Earth's axial tilt (obliquity), the rotational wobble that controls when Earth is closest to the Sun (precession), and the ellipticity of Earth's orbit around the Sun (eccentricity). We know the timing of these orbital changes with great accuracy.

Evidence for ice-age cycles, and the terminations that separate them, is best preserved in ocean sediments. For decades, we have been drilling cores from the ocean floor to study oxygen isotopes in tiny fossil protists called foraminifera, which build calcareous shells from seawater. During terminations, the decrease in Earth's total ice volume alters the oxygen-isotope budget of seawater. Foraminifera record these variations. Some of the best ocean records have been drilled off the coast of Portugal, where ice-sheet meltwaters reach. Detailed measurements on foraminifera and other microfossil remains show precisely how each termination plays out. To test the orbital theory, however, we need to determine precisely *when* each termination occurs. It is only possible to date ocean sediments for the last termination (between 18,000 and 7,000 years ago). For older ones, the answers reside underground.

Stalagmites are calcium carbonate mineral deposits that form in caves. The drip waters they grow from originate as rainfall above the cave. Each milliliter of that water preserves information about the regional climate, with the exact detail varying from place to place according to atmospheric circulation and distance from the ocean. We studied stalagmites from Antro del Corchia (Tuscany, Italy). Most of Tuscany's weather arrives from the west: when the North Atlantic coughs, Tuscany sneezes. This climate connection also applied in the past.

During a termination, the vast meltwater pulse from decaying ice sheets freshens the surface ocean water. Air masses draw-off moisture from this water and carry its distinctive isotope meltwater signature eastwards, delivering it as rain and snow to mountains above Corchia Cave. The signature is relayed to the cave's stalagmites via drip waters, turning these crystal formations into termination recorders. Critically, the age of stalagmites can be accurately determined using a radiometric technique called uranium-series dating. This allows terminations to be fixed to an accurate time scale – ready for comparison with orbital variations.

We studied several stalagmites from Corchia Cave that recorded two consecutive terminations: one which started about 960,000 years ago and another around 875,000 years ago. The time gap between them was previously thought to be 100,000 years, equivalent to the average time it takes for the Earth to complete one orbital eccentricity cycle. Our data indicate a spacing of about 85,000 years or two obliquity cycles. Both terminations started when Earth's tilt angle was relatively high, further implicating changes in Earth's tilt as an essential trigger.

What about younger terminations? We compared our results with those from an earlier study on the last nine major episodes of ice-sheet collapse, representing the last 40,000 years. Here, the stalagmites were from caves located in China, where the climate is heavily influenced by the Asian monsoon. How do Chinese caves record terminations when the North Atlantic is so far away? When the great ice sheets collapse, the flux of cold freshwater into the North Atlantic causes large-scale atmospheric re-organisation. A by-product of this is a weaker Asian monsoon, which is recorded in the oxygen isotopes of the stalagmites. Radiometrically dating these weak monsoon intervals constrains the age of the terminations.

Comparing the stalagmite data from the two regions with corresponding orbital information reveals that summer insolation changes in the high northern latitudes caused by approximately equal contributions of obliquity and precession provide the most consistent explanation for termination timing. The comparison also reveals that the time it takes for a termination to complete depends on the status of insolation when the termination commences: when summer insolation is already high, terminations are achieved rapidly.

The next task is to tackle terminations prior over the preceding one million years. These seem to be spaced at 40,000-year intervals, again implicating obliquity. But we may be in for a surprise – time will tell.