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Continuous 500,000-Year Climate Record from Vein Calcite in Devils Hole, Nevada

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Oxygen-18 ($\delta^{18}O$) variations in a 36-centimeter-long core (DH-11) of vein calcite from Devils Hole, Nevada, yield an uninterrupted 500,000-year paleotemperature record that closely mimics all major features in the Vostok (Antarctica) paleotemperature and marine $\delta^{18}O$ ice-volume records. The chronology for this continental record is based on 21 replicated mass-spectrometric uranium-series dates. Between the middle and latest Pleistocene, the duration of the last four glacial cycles recorded in the calcite increased from 80,000 to 130,000 years; this variation suggests that major climate changes were aperiodic. The timing of specific climatic events indicates that orbitally controlled variations in solar insolation were not a major factor in triggering deglaciations. Interglacial climates lasted about 20,000 years. Collectively, these observations are inconsistent with the Milankovitch hypothesis for the origin of the Pleistocene glacial cycles but they are consistent with the thesis that these cycles originated from internal nonlinear feedbacks within the atmosphere–ice sheet–ocean system.

Since Louis Agassiz's startling claim 155 years ago that a polar ice sheet once covered much of Europe (*1*), the study of the timing, extent of, and causation for the Pleistocene ice sheets, as well as the prediction of future ice ages, has remained among the most basic, yet speculative, fields of earth science. In the past two decades, there has been a major interdisciplinary effort to tackle the ice-age puzzle anew, an effort driven in great part by the availability of new information and analytical methods (*1*). The paleontology and isotopic composition of hundreds of deep-sea sediment cores have been analyzed in order to reconstruct the secular variation of climate during the Pleistocene; ice-age climates have been simulated with the use of process-driven general circulation models; the CO_2 content of the atmosphere during the past 160,000 years has been documented by analysis of an ice core from Antarctica; and a once rejected theory for the onset of ice ages—the Milankovitch hypothesis—was revived (*1–3*). We now appreciate that numerous interrelated conditions on land and in the oceans and atmosphere and the attendant feedbacks among them were involved in the recurrence of ice ages during the Pleistocene. Factors identified as potentially relevant include changes in: magnitude and distribution of ocean currents; ocean productivity; sea-surface temperatures; the location of the atmospheric polar and subtropical jet streams; latitudinal gradients in atmospheric temperature and wind; cloud cover; atmospheric concentrations of dust, CO_2, CH_4, and water vapor; and orbitally controlled variations in solar insolation (*1–3*). In addition, subsidence and rebound of the earth's crust in response to ice-sheet loading; the extent and thickness of the continental ice sheets and of sea ice; and the increase in coastal plain areas attendant to sea-level lowering could also have an effect. A solution to the ice-age puzzle will require deciphering which of the above factors, or more likely groups of factors, comprise the principal processes driving the waxing and waning of the Northern Hemisphere ice sheets.

One of several major obstacles to solving the ice-age riddle has been the absence of radiometrically well-dated paleoclimate records spanning several glacial cycles. In this article, we present such a record derived from vein calcite that precipitated from ground water in the Great Basin. This record enables us to determine accurately the timing and duration of the major climate shifts of the mid-to-late Pleistocene and, in turn, to comment on the validity of two theoretical approaches to the ice-age problem—the Milankovitch hypothesis (*1*) and nonlinear dynamical simulations of Pleistocene climates (3).

Devils Hole and Its Climate Record

Devils Hole is an open fault zone adjacent to a major ground-water discharge area (Ash Meadows) in south-central Nevada; it is located approximately 115 km west-northwest of Las Vegas, Nevada (Fig. 1). To depths in excess of 130 m below the water table (which is 15 m below land surface), this open fissure is lined with a thick (>0.3 m) layer of dense mammillary vein calcite that precipitated continuously from calcite-supersaturated ground water over the past 500,000 years (4). A 36-cm long core (DH-11) of vein calcite was recovered from about 30 m below the water table by SCUBA divers and a submersible air-powered coring machine designed for operation in the tight (0.5 to 2 m) confines of the steeply (>70°) dipping fault zone that forms Devils Hole. Like vein calcite sample DH-2, which yielded our initial 250,000-year record (5), DH-11 is pure calcite and contains no apparent depositional hiatuses nor any evidence of calcite recrystallization, as determined by detailed thin-section petrography (6). Further evidence that DH-11 behaved as a geochemically closed system during the past half-million years is presented in (*7*).

We milled 285 samples at a sampling interval of 1.26 mm along the length of core DH-11 and analyzed each for $\delta^{18}O$ and carbon-13 ($\delta^{13}C$). The $\delta^{18}O$ data were plotted against their distance from the free face of the core and the resulting curve was used to select 14 climatically interesting locations for alpha-spectrometric uranium-series dating, and, subsequently, 21 intervals for mass-spectrometric (MS) uranium-series dating (*7*). Using the more precise MS ages, we interpolated the age of each of the 285 samples analyzed for $\delta^{18}O$ (Fig. 2). The sampling interval (1.26 mm) represents an average time interval of about 1800 years.

The Devils Hole $\delta^{18}O$-time curve (Fig. 2) clearly displays the sawtooth pattern characteristic of marine $\delta^{18}O$ records that have been interpreted to be the result of the waxing and sudden waning of Northern Hemisphere ice sheets during the Pleistocene (8). But what caused the $\delta^{18}O$ variations in DH-11 shown on Fig. 2? As discussed in (5), the $\delta^{18}O$ variations in DH-11 calcite most likely principally reflect isotopic variations in atmospheric precipitation falling on ground-water recharge areas tributary to Devils Hole, specifically the Spring Mountains, Pahranagat Valley (and tributary areas) and possibly the Sheep

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Range (Fig. 1). That is, $\delta^{18}O$ values are conserved during movement through this relatively low-temperature (10° to 35°C) regional ground-water flow system (*5*, *9*). The isotopic variations in atmospheric precipitation are—to a first approximation (*5*, *10*)—believed to reflect changes in average winter-spring land surface temperature, the season during which recharge is most likely to have occurred in the southern Great Basin; the highest $\delta^{18}O$ values on Fig. 2 reflect warm temperatures and the low values reflect a cold climate (*10*); each data point on Fig. 2 represents a ~2000-year average.

The DH-11 record provides minimum ages of climatic events. This is because the U-series techniques date the time when the calcite precipitated out of a parcel of water in Devils Hole, not when that parcel (with its $\delta^{18}O$ signature) fell as precipitation in the recharge areas 80 to >160 km to the east and northeast. These respective events are offset by the time required for the water to traverse the flow system. Thus, the true age of any point on the $\delta^{18}O$ curve (Fig. 2) is equal to the measured age given on the abscissa plus the ground-water transit time through the aquifer. Just how long is the transit time? In our earlier report (*5*), we cited reconnaissance ^{14}C values that suggested that ground water currently discharging at the Ash Meadows oasis adjacent to Devils Hole had been underground about 10,000 to 30,000 years; recent work suggests that the ^{14}C age is 15,000 to 20,000 years (*11*). Five other lines of evidence (*12*), however, argue for considerably shorter travel times, less than 10,000 years, and perhaps on the order of several thousands of years.

Comparison with Other Records

To see to what degree our Great Basin paleotemperature record reflects major mid-to-late Pleistocene climatic shifts, we compare it with two other continuous and well-established stable isotope records, SPECMAP, the marine $\delta^{18}O$ standard (*13*), and the Vostok, Antarctica (*14*), ice core deuterium (δD) record (Fig. 3). We use the δD variations for Vostok because they are considered a somewhat better indicator of temperature changes than $\delta^{18}O$ values (*14*); however, a normalized plot of Vostok $\delta^{18}O$ values would, for our purposes, be indistinguishable from the δD curve shown. The overall similarity of the three records is striking, especially considering that they were obtained from different materials and were dated by different means. SPECMAP is interpreted as a record of Northern Hemisphere ice volume (*13*) deduced from $\delta^{18}O$ values of planktonic foraminifera. It is indirectly dated by "tuning"; that is, dates initially assigned by interpolation between three radiometric control points were shifted iteratively to obtain a new chronology that best corresponded to the earth's orbital oscillations (*13*). The Vostok record (*14*) reflects mean annual air temperature as recorded in glacial ice in Antarctica at 78°S and an altitude of 3488 m; it is indirectly dated with an ice-sheet flow model (*14*) and assumptions regarding snow accumulation and thinning rates. The DH-11 record reflects mean winter-spring air temperature (*5*) in the southern Great Basin, as recorded by $\delta^{18}O$ values of directly

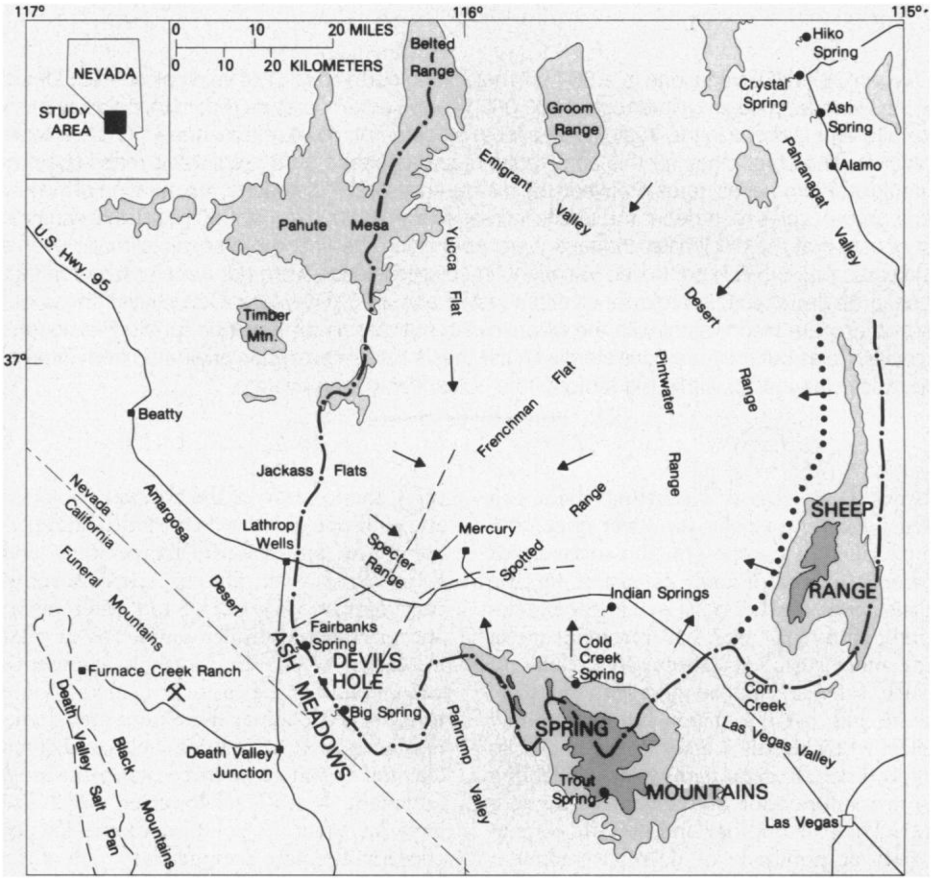

Fig. 1. Index map of southcentral Great Basin. Major mountains are shaded: heavy shading denotes altitudes of 2400 to 3600 m; light shading denotes altitudes of 1800 to 2400 m, ridges <1800 m are designated by name only. Dashed and dotted line, approximate boundary of Ash Meadows ground-water basin (*33*); dotted line, alternative eastern boundary (*11*). Arrows denote general direction of ground-water flow as inferred from potentiometric map (*33*). Dashed lines bound major trough in potentiometric surface.

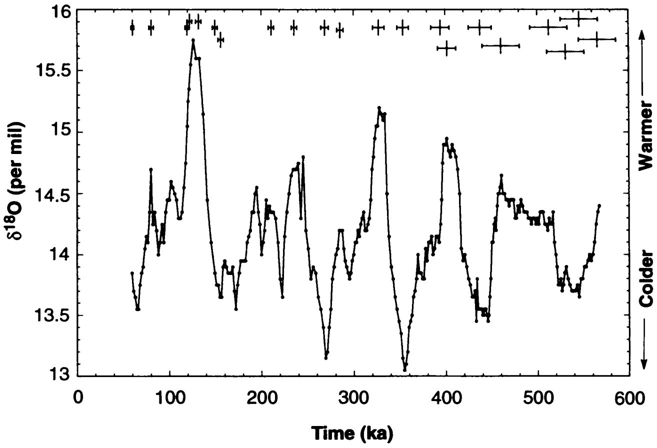

Fig. 2. Variations in $\delta^{18}O$ values along 36-cm-long core DH-11. Each dot represents a calcite sample analyzed for $\delta^{18}O$ values; ages were assigned to the $\delta^{18}O$ data by interpolating between 21 MS uranium-series-dated intervals (*7*). Distribution of the MS ages along the core is shown by vertical lines below upper margin; error bars (2σ) shown by horizontal lines. Details on the MS dating are in (*7*). Precision of $\delta^{18}O$ data (1σ) is 0.07 per mil, reported relative to VSMOW on a scale normalized to $\delta^{18}O$ of SLAP = −55.5 per mil (*34*).

dated vein calcite of ground-water origin (*7*).

All three records (Fig. 3) display relatively rapid shifts from full-glacial to interglacial climates followed by a gradual return to full glacial conditions. The approximate midpoints of the transitions from full glacial to peak interglacial climates have been called "terminations" (*8*) (Fig. 3). The DH-11 record, which begins about 566 ka (thousand years ago) and ends at 60 ka, spans three full glacial cycles and the first half of the most recent cycle. In contrast to the youngest 460,000 years of record, the oldest 100,000 years of the DH-11 and SPECMAP records show minimal variation in $\delta^{18}O$ values (Fig. 3); there is little justification, from curve geometry, for a termination in this oldest interval, and none is shown.

In spite of the strong similarity between these paleoclimate records, there are significant differences among them with respect to curve configuration. For example, during the period between about 240 and 190 ka (marine isotope stage 7) successive peaks in the SPECMAP record increase in height with decreasing age (see slope of dashed line connecting peaks on the SPECMAP curve, Fig. 3). This change indicates that conditions warmed rather than cooled; in the DH-11 record, in contrast, the peaks decrease in height with decreasing age (see slope of dashed line on DH-11 curve) as expected during a buildup to full glacial climates. A second difference is in the robustness of termination III. In the SPECMAP record, this termination is subdued and amounts to a shift of only two standard deviations in $\delta^{18}O$ values, which is about half that of terminations I, II, IV, or V. In the DH-11 record, in contrast, termination III is bold, and $\delta^{18}O$ values shift by more than three standard deviations. A third difference is that the DH-11 record suggests that interglacial climates became slightly warmer from 410 to 120 ka (see dashed-dotted sloping lines in Fig. 3); such warming is barely discernible in the SPECMAP $\delta^{18}O$ curve.

Sarnthein and Tiedemann (*15*) presented high-resolution planktonic and benthic $\delta^{18}O$ records from Ocean Drilling Program Site 658, off the northwest coast of Africa. The average sedimentation rate at this site is more than four times that of the five cores used to construct the SPECMAP curve (*13*). In the records from site 658, the peaks in marine isotope stage 7 decrease in height with decreasing age, and termination III is clearly developed. The composite marine chronology of Williams *et al.* (*16*) also shows these two prominent features, which are shown in both the DH-11 and site 658 records but are missing from the SPECMAP record. The contrasts with the SPECMAP record cited above are not mentioned in order to question its established position as a norm for numerous marine records but rather to show that some major features of the DH-11 record not present in the SPECMAP record are definitively present in other equally detailed marine $\delta^{18}O$ records.

The overall similarity of the DH-11 record to the SPECMAP record, to other equally detailed marine $\delta^{18}O$ records (*15*, *16*) and to the Vostok record, is the basis for our conclusion that the climate record from DH-11 closely reflects global climate changes (*17*). This is not to say that the climate changes in these records are necessarily synchronous or that (in the case of Vostok and DH-11 records) they record equivalent temperature changes. By "global" we mean that major features of the DH-11 (or Vostok) record appear to closely mimic the major features in the marine record, which has generally been accepted as representing global climate change. Although local and regional meteorological factors are undoubtedly present in the Vostok and DH-11 records, they have not interfered with a definitive expression of the full glacial, interglacial, stadial, and interstadial climates seen in the marine record during the period 570 to 60 ka.

Timing of Terminations

There are significant differences in the timing of the terminations among the DH-11, Vostok, and SPECMAP records (Fig. 3). These differences bear directly on the Milankovitch hypothesis, which attributes Pleistocene climatic cycles to orbitally controlled variations in solar insolation (*1*). Termination II occurs at 140 ± 3 (2σ) ka in the DH-11 record, at 140 ± 15 ka in the Vostok record (*14*), and at 128 ± 3 ka in the SPECMAP record (*13*). (The uncertainty in the DH-11 record is in the 2σ uncertainties on the MS uranium-series dates; other dates and uncertainties are from the sources cited.) Termination III

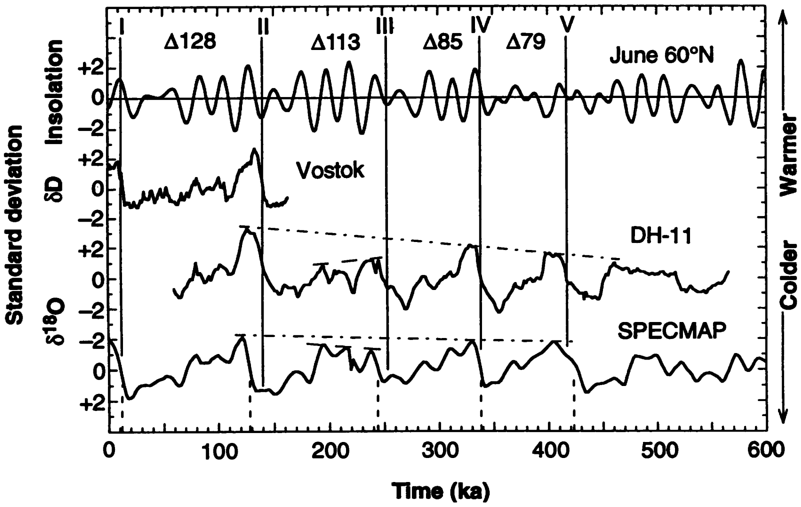

Fig. 3. Comparison of marine SPECMAP (35) and DH-11 $\delta^{18}O$ records, Antarctica ice sheet δD record from Vostok (*14*), and June 60°N insolation (*22*) for the middle-to-late Pleistocene. All records have been normalized to standard deviation units for the length of record shown. Time scales are as given in sources cited. Solid vertical lines represent terminations (that is, approximate midpoints of deglaciations) in the DH-11 and Vostok curves; dashed vertical lines are terminations in the SPECMAP record (*16*). Roman numerals designate terminations, following Broecker and Van Donk (*8*). Numbers beneath upper margin (Δ79, Δ85, and so forth) represent the time between terminations in the DH-11 and Vostok records. Short dashed and dashed-dotted sloping lines are described in the text. Ages of terminations (and other features of interest) shown by DH-11 curve are minimum values because of the ground-water residence time in the Ash Meadows basin (see text).

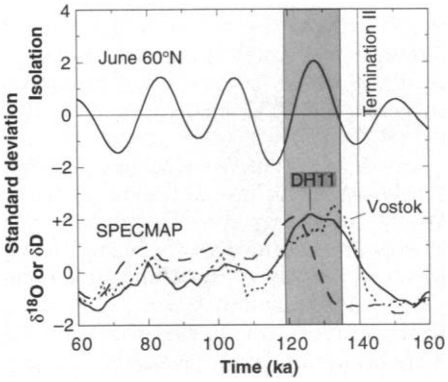

Fig. 4. Superposition of DH-11, Vostok, and SPECMAP curves for the period 160 to 60 ka and comparison with June 60°N insolation and sea-level high stands. Normalization done with reference to interval 160 to 60 ka. Sources of curves are as in Fig. 3. Shading represents time of sea-level high stands (at or above modern levels) determined by MS uranium-series–dated coral reef terraces on Huon Peninsula, Indonesia (*19*), and Bahamas (*20*).

(Fig. 3) occurred at about 253 ± 3 (2σ) ka in the DH-11 record and at about 244 ± 3 ka in the SPECMAP record. These differences between the timing of terminations II and III in the DH-11 and SPECMAP records are minimum values because the ground-water travel time to Devils Hole (see above) would increase the differences by at least several thousand years. Because of the larger uncertainty of the DH-11 dates in the vicinity of terminations IV and V (Figs. 2 and 3), the timing of these two terminations in the DH-11 and in SPECMAP records are not significantly different.

The timing of deglaciations has been widely attributed (*1, 2, 18*) to the influence of major peaks in high-latitude summer insolation in the Northern Hemisphere; specifically, the exceptional peaks at 128 ± 1 and 220 ± 1 ka (Fig. 3). However, the DH-11 record does not support this interpretation (Fig. 3). The warming associated with terminations II and III in the DH-11 record, and II in the Vostok record, began well before the start of above average insolation. For example, the warming preceding termination II began in the DH-11 record around 150 ka at a time of falling insolation; when insolation rose to its average value, at about 135 ± 1 ka, the $\delta^{18}O$ value in ground water depositing calcite at Devils Hole was nearly at its peak value (Fig. 4). In the vicinity of termination III, the temperature rise recorded in DH-11 calcite began, and was two-thirds complete during a period of near average insolation (270 to 248 ka). Furthermore, if we take ground-water residence times into account, the amount that DH-11 terminations precede the cited maxima in June 60°N insolation is at least several thousand years greater than shown. In contrast, the deglaciation in the SPECMAP record, near the time of termination II, slightly lags the insolation curve, as would be expected if insolation triggered the $\delta^{18}O$ changes seen in this record (Fig. 3).

Sea-level variations, which are independently measured, are consistent with the DH-11 chronology (Fig. 4). Sea level had already attained modern (or higher) levels by about 135 ka at the Huon Peninsula, Indonesia (*19*), and by 132 ± 1 (2σ) in the Bahamas (*20*), which was 4000 to 7000 years before insolation peaked at 128 ± 1 ka. In contrast, Holocene sea level began its rise toward modern levels around 19 ka (*21*) but did not approach modern levels until 6 ka, or more than 5000 years after the most recent insolation maximum at 11 ka (*21*). If the time required for sea-level rise during termination II was approximately similar to the time (~13,000 years) required during termination I, then the initiation of the sea-level rise that led to the high stands at 132 to 135 ka would have begun around 145 to 150 ka at a time of decreasing insolation (Figs. 3 and 4). This timing is in agreement with the DH-11 record, which shows initiation of warming at around 150 ka. Thus, the DH-11 $\delta^{18}O$ record, and the MS dated sea-level high stands at Huon Peninsula and in the Bahamas support our contention that the major insolation maximum at 128 ± 1 ka did not trigger termination II. Additionally, the SPECMAP record indicates that full glacial conditions occurred at a time (132 to 135 ka) when sea level was apparently at (or above) modern levels (Fig. 4) and when the DH-11 record indicates that there was an interglacial climate. Thus, the SPECMAP chronology is inconsistent with these records and may not simply lag the DH-11 and Vostok records by 10,000 years (*17*).

In contrast, for Termination IV, both the DH-11 and SPECMAP records are consistent and coincide with a major buildup in insolation (Fig. 3); however, the uncertainty in the ages for DH-11 at this time (Fig. 2) is relatively large.

Termination V (Fig. 3) occurred at a time [417 ± 12 (2σ) ka for DH-11 and 423 ± 3 ka for SPECMAP] of only nominal variation in insolation. Berger (*22*) has shown that for all latitudes and months in both hemispheres insolation variations were greatly subdued during the period 450 to 350 ka because of the combined effects of near zero eccentricity and minor variation in the precessional parameter (*22*).

In summary, three of the four terminations recorded by the DH-11 record either preceded (II and III) or are not associated with (V) major insolation peaks; uncertainty in our dates precludes relating termination IV to insolation. We thus conclude that variations in Northern Hemisphere solar insolation did not directly force deglaciations. Insolation may not even be a decipherable nonlinear factor leading to deglaciation, as suggested by the occurrence of a prominent termination (V) (and subsequent buildup to full-glacial climates) in both the DH-11 and SPECMAP records at a time of minimum insolation variations at all latitudes and months in both hemispheres (*23*).

Obliquity and precession periodicities are evident in the DH-11 record (*24*). Such periodicities suggest that although solar insolation may not be the primary determinant of the onset of glacial-interglacial shifts, astronomical geometry could still be one of several factors contributing to Pleistocene paleoclimate changes. Yet, such 40,000- and 20,000-year cycles have been widely reported to occur in geologic records that predate the onset of Northern Hemisphere glaciation by millions to more than 100 million years (*25*).

Duration of Interglacial Climates

There are major differences in the duration of peak interglacial climates between the DH-11 and Vostok record, on the one hand, and the SPECMAP record, on the other. Lorius *et al.* (*14*) noted that the duration of marine isotope substage 5e—the interglacial maximum following termination II, called the Sangamon in the United States and the Eemian in Europe (*26*)—is approximately 24,000 years in the Vostok record and 11,000 years in the SPECMAP record. Lambeck and Nakada (*27*) applied glaciohydroisostatic models to global sea-level data and concluded that isotope substage 5e lasted at least 15,000 years. In contrast, this substage has been widely considered to have lasted 11,000 years, or one-half of a precessional cycle (*28*). To analyze these differing opinions, we define this interglacial as the time interval during which the $\delta^{18}O$ value (or δD) resided in the upper one-third of its deglaciation amplitude (for example, for substage 5e, the time during which $\delta^{18}O$ on Fig. 2. equaled or exceeded 15.0 per mil). For this arbitrary definition of interglacial, the duration of the Sangamon is found to have been 18,000, 18,000, and 14,000 years in the DH-11, Vostok, and SPECMAP records, respectively; and, the three interglacial substages following terminations III to V would have lasted, respectively, 21,000, 18,000, and 20,000 years in the DH-11 record and 8,000, 30,000 and 30,000 years in the SPECMAP record. An alternate method of estimating the duration of the interglacial climates—using the difference in age of the midpoints of the ascending and descending limbs of the $\delta^{18}O$ curves—yields similar results. The finding that interglacial climates apparently lasted about 20,000 years may be of practical importance (*29*).

The 100,000-Year Cycle and Implications

Much has been written about the origin of the dominant 100,000-year cycle present in mid-to-late Pleistocene isotopic records, a cycle not predicted by the Milankovitch hypothesis (*1, 2*). Some workers have attributed its origin to a nonlinear response to external, that is to orbital insolation forcing (*13*), while others have proposed that it results from free oscillations driven by internal feedbacks in a complex nonlinear atmosphere–ocean–ice sheet system (*13, 30*). Still other models invoke both internal and external forcing to explain the 100,000-year cycles (*13, 30*).

As shown in Fig. 3 the duration of glacial cycles, based on the DH-11 record, increased from 79,000 years between terminations V and IV to 128,000 years between

II and I (*31*). The SPECMAP record also shows an increase in the duration of these cycles between terminations V and II (Fig. 3), as does the independently dated marine δ^{18}O chronology of Williams *et al.* (*16*); however, this increase ends in these marine records between terminations II and I. The DH-11 data, and to a lesser extent the marine records, thus suggest that middle-to-late Pleistocene climate did not arise from a strictly stationary process, a finding previously noted for the marine record (*32*). Additionally these low-frequency cycles of increasing duration in the DH-11 record are apparently superimposed on a much longer-lived transient warming (see sloping dashed-dotted line on Fig. 3).

In all three time series (Fig. 3), the trough centered at 65 ka (marine isotope stage 4) indicates that the climate then was just as cold (and presumably ice volume as large) as during the glacial maxima immediately preceding some of the terminations. The prominent trough at 222 ka in the DH-11 record (Figs. 2 and 3) is another example. These troughs suggest that climates of full glacial severity also occurred at times other than immediately before terminations. Such events of full glacial magnitude, plus our observations regarding the increasing length of the so-called 100,000 year cycles, and the timing of terminations, support the contention of nonlinear dynamicists that Pleistocene climate phenomena are aperiodic and therefore that their timing is probably unpredictable (*32*).

In summary, the DH-11 δ^{18}O paleoclimate record—anchored by 21 MS uranium series dates—is inconsistent with the Milankovitch hypothesis that orbitally controlled variations in solar insolation play a direct role in Pleistocene climate change. The hypothesis fails to predict the timing of deglaciations during the period 500 to 100 ka. During the middle-to-late Pleistocene the increase in the duration of glacial cycles from about 80,000 to 130,000 years suggests that climate shifts were aperiodic. Interglacial climates lasted on the order of 20,000 years.

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4. The neotectonic, hydrologic, and geochemical setting of this cave is discussed by A. C. Riggs, P. T. Kolesar and R. J. Hoffman, in preparation.
5. I. J. Winograd, B. J. Szabo, T. B. Coplen, A. C. Riggs, *Science* **242**, 1275 (1988); for discussion, see comment by R. G. Johnson and H. E. Wright, Jr. [*ibid.* **246**, 262 (1989)] and reply by I. J. Winograd and T. B. Coplen (*ibid.*, p. 262).
6. Core DH-11, as removed from Devils Hole, was 42 cm long. The innermost (or oldest) 6 cm of this core is fractured and stratigraphically complex and was not used in our study. The useable outermost 36 cm of the core consists of large crystals (up to 2.34 cm long and 2 to 3 mm wide) of calcite oriented with the long axis approximately perpendicular to the bedrock wall. Each large crystal has a complex internal structure in which many smaller (2 to 4 mm long and 0.25 to 1 mm wide) crystallites are arranged like closely spaced teeth on a comb. The long axes of the crystallites attach to the back of the comb at a high (>70°) angle. The *c*-axes of the crystallites are oriented at high angles (>60°) to the direction of elongation, so the crystallites are length-slow. The deposit is dense, with a porosity very much less than 1%, probably because of the slow growth rate (about 0.7 mm per 1000 years). There is no evidence for recrystallization of the calcite and except for one interval—corresponding to an age of about 400 ka—no evidence of a hiatus in calcite-crystal growth. At a distance of 221 to 224 mm from the free (outer) face of the core are two parallel zones marked by abrupt crystal terminations and by nucleation of many small crystals on those terminations. To determine the magnitude of this possible hiatus, we dated samples taken at 219 and 227 mm from the free face of the core; these samples yielded ages of 395 ± 10 (2σ) and 402 ± 10 (2σ) ka, respectively (*7*). These ages are statistically indistinguishable, suggesting that the interruption in crystal growth was short-lived. That the zones of the crystal terminations do not represent a hiatus is indicated, both in thin section and in slabs of the core, by the discontinuous nature of these zones; these breaks in crystal growth may instead reflect a response to jointing caused by the ongoing tectonic extension that formed Devils Hole (*4*). The δ^{18}O data (Fig. 2) and the δ^{13}C record (T. B. Coplen *et al.*, in preparation) similarly give no hint of a hiatus in the vicinity of 400 ka. In summary, thin-section examination indicates that the calcite forming core DH-11 precipitated continuously between 566 and 60 ka (Fig. 2) and has not recrystallized. It is a mystery why the precipitation of vein calcite on most submerged surfaces in Devils Hole stopped at approximately 60 ka even though the water in this cave remained supersaturated with respect to calcite (*4*). One possible explanation [A. C. Riggs, in *Proceedings of the Desert Fishes Council*, E. P. Pister, Ed. (Desert Fishes Council, Bishop, CA, 1991), vols. 20 and 21, pp. 47–48] is that Devils Hole opened to the surface about 60 ka and the consequent introduction of inorganic ions introduced from the land-surface environment or organic compounds generated by the aquatic flora and fauna that colonized the newly available habitat or other compounds stopped the widespread precipitation of calcite from the slightly supersaturated waters.
7. K. R. Ludwig *et al.*, *Science* **258**, 284 (1992).
8. W. S. Broecker and J. Van Donk, *Rev. Geophys. Space Phys.* **8**, 169 (1970).
9. Since publication of (*5*), we have obtained evidence that changes in ground-water temperature in Devils Hole did not affect (by changing oxygen isotope fractionation between $CaCO_3$ and H_2O) the δ^{18}O value in the vein calcite. One of us (K.M.R.) analyzed the deuterium (D) in fluid inclusions of vein calcite representing the peak and trough in δ^{18}O values at about 130 and 160 ka, respectively (Fig. 2). A δD difference of 14 per mil was found. This difference—when coupled with knowledge that D (which is not part of the calcite lattice) should be independent of isotopic fractionation of oxygen during calcite precipitation—requires that the δ^{18}O value in Devils Hole ground water changed by 1.8 per mil if temperature variations did not influence the isotopic fractionation of oxygen. A δ^{18}O variation of 2.1 per mil is observed between the cited peak and trough (Fig. 2), which is consistent with the conclusion that ground-water temperature variations in Devils Hole do not account for the δ^{18}O shifts in our record; two other reasons for this conclusion were given in (*5*).
10. The relation between the mean δ^{18}O of precipitation and mean land surface temperature is complex; that is, variations in moisture sources, ocean isotopic composition and temperature, and synoptic climatologic and other factors undoubtedly jointly control the δ^{18}O value of precipitation at a site, but the relations are not understood (P. M. Grootes, in paper presented at the Chapman Conference of Continental Isotope Indicators of Climate, Jackson Hole, WY, 10 to 14 June 1991). Even so, an empirical relation between δ^{18}O values in precipitation and temperature is well-documented globally for mid-to-high latitudes [See for example: Y. Yurtsever and J. R. Gat, *IAEA Tech. Rep. 210*, 103 (1981); J. Jouzel *et al.*, *J. Geophys. Res.* **92**, 14,739 (1987); D. A. Fisher, *Ann. Glaciol.* **14**, 65, (1990); S. J. Johnson, W. Dansgaard, J. W. C. White, *Tellus* **41B**, 452 (1989)]. This empirical relation has also been documented for mid-latitude North American ground waters by C. J. Yonge *et al.* [*Chem. Geol.* **58**, 97 (1985)], who compared the δ^{18}O values of cave-seep waters with cave temperatures; they obtained virtually the same relation obtained by Yurtsever and Gat for precipitation δ^{18}O and surface temperature.
11. J. M. Thomas and M. D. Dettinger, manuscript in review.
12. Evidence suggesting that ground-water residence time is considerably less than inferred from ^{14}C dating includes: (1) Several dozen ^{14}C-dated water samples from wells and springs around the Spring Mountains show no relation of either δD or δ^{18}O values with ^{14}C age over the past 20,000 years (*11*). These data can mean either that: (i) there was no variation in stable isotope content with time, a condition clearly disproven by the Devils Hole and other records from the southwestern United States (*5*); (ii) the ^{14}C ages are correct, but Holocene climates were achieved well before the widely accepted time frame of 10 to 12 ka; or (iii) the ^{14}C ages are incorrect and all of these ground waters are of Holocene age and therefore show little stable isotopic variation. Of these possibilities, the third appears most plausible. (2) Ground-water residence times derived from hydrogeologic data are one or more orders of magnitude less than indicated by ^{14}C dating (*11*). (3) The DH-11 δ^{18}O curve is synchronous (within a few thousand years) with the Vostok δD curve to 150 ka and with the marine SPECMAP curve for ages younger than 110 ka (Figs. 3 and 4); similarly, DH-11 δ^{18}O data agree closely with sea-level high stands as early as 135 ka (Fig. 4). (4) In view of the known hydraulic heterogeneity of the regional carbonate aquifer [I. J. Winograd and W. Thordarson, *U.S. Geol. Surv. Prof. Pap. 712-C* (1975); I. J. Winograd and F. J. Pearson, Jr., *Water Resour. Res.* **12**, 1125 (1976)], and the likely input of water into the aquifer from multiple recharge areas at various distances from Devils Hole, hydrodynamic dispersion or mixing of recharge sources (with differing ages and isotopic contents) should have damped out all but the major peaks and troughs in δ^{18}O values displayed in Fig. 2 during the 80- to >160-km journey of ground water from recharge to discharge areas. It is, therefore, remarkable to see a δ^{18}O signal (Fig. 2) at the end of the flow system that so closely resembles the SPECMAP and Vostok records (Fig. 3). Prominent secondary troughs, some as short as 10,000 years duration, are clearly evident, for example, the troughs centered at about 172 and 200 ka (Fig. 2). A throughput of several volumes of aquifer water would be necessary within 10,000 years in order to preserve these sharply defined δ^{18}O troughs. This situation suggests that ground-water residence times are a fraction of 10,000 years. (5) Geochemical modeling by one of us (T.B.C.) and in (*11*) demonstrates that calculated ^{14}C ages of ground water are extremely sensitive to input parameters, and the actual transit time could be less than 10,000 years.
13. J. Imbrie, A. McIntyre, A. Mix, in *Climate and Geosciences*, A. Berger, S. Schneider, J.-Cl. Du-

plessy, Eds. (Kluwer, Boston, 1989), pp. 121–164.

14. C. Lorius *et al.*, *Nature* **316**, 591 (1985); J. Jouzel *et al.*, *ibid.* **329**, 403 (1987). The δD curves in Figs. 3 and 4 were taken from Fig. 1 of Jouzel *et al.* (1987). J. R. Petit *et al.* [*Nature* **343**, 56, (1990)] assigned an alternate chronology to the Vostok stable isotope time series than that used by the cited original workers. They identified and tentatively correlated full-glacial dust horizons in both Vostok and in deep-sea core RC11-120, which had been dated by reference to the SPECMAP record. They then assigned the marine chronology to Vostok, resulting, for example, in a 128 ka age for termination II. Petit *et al.* noted that their revision of the Vostok chronology was independent of absolute dating. Both chronologies continued to be used (*3*). That the original Vostok chronology, used in this paper, is probably more correct is indicated by its correspondence both to the DH-11 record and to MS uranium-series ages for sea-level high stands for the period 135 to 119 ka (see below and Fig. 4).
15. M. Sarnthein and R. Tiedemann, in *Proc. Ocean Drill. Prog. Sci. Results Leg. 108*, W. Ruddimann *et al.*, Eds. (University of Texas, College Station, TX, 1989), vol. 108, chap. 12.
16. D. F. Williams, R. C. Thunell, E. Tappa, D. Rio, I. Raffi, *Paleogeogr. Paleoclimatol. Paleoecol.* **64**, 221 (1988).
17. Unlike the SPECMAP record, the DH-11 record is not physically correlated to a globally averaged phenomenon such as ice volume (*13*). Hence, the DH-11 record may reflect local or regional rather than global paleotemperature. We conclude that a local response is unlikely, first, because the MS uranium-series–dated sea-level high stands for the period 135 to 119 ka correlate well with the warmest interval in the DH-11 record (see below and Fig. 4) and thus indirectly tie the Devils Hole record to global ice volume; this correspondence also justifies our use of the globally defining term, "termination," when discussing the DH-11 record. Second, terminations II and III in the DH-11 record precede those in the SPECMAP record by about 10,000 years (Fig. 3). Given that SPECMAP is widely accepted as a global record, we are faced with a dilemma. How could a purported local or regional record precede the global marine record? Two possibilities come to mind. We suggest elsewhere in this paper that the dating of the SPECMAP record may be in error for ages older than 110 ka. Accordingly, we leave open the possibility that when the SPECMAP record is dated radiometrically, key climatic events in the marine record might be seen to lead related temperature shifts in DH-11 record. Such a lead by the SPECMAP record might support Kutzbach's suggestion that the climate of the Southwest was significantly influenced by Northern Hemisphere ice-sheet deflection of the jet stream [J. E. Kutzbach, in *North America and Adjacent Oceans During the last Deglaciation*, vol. K-3 of the *Geology of North America*, W. F. Ruddimann and H. E. Wright, Eds. (Geological Society of America, Boulder, CO, 1987), pp. 425–446]. A second possibility is that the Devils Hole and SPECMAP chronologies are both correct, but that the DH-11 record reflects a global temperature signal that leads global ice volume (represented by the SPECMAP record) by 10,000 years. For example, sea-surface temperature (SST) variations in the Southern Hemisphere lead variations in marine δ^{18}O values by several thousands of years (*13*), whereas CO_2 and temperature variations in the Vostok core apparently lead marine δ^{18}O changes by at least 4000 years [T. Sowers, M. Bender, D. Raynaud, Y. S. Korotkevich, J. Orchado, *Paleoceanography* **6**, 679 (1991)]. And, in the DH-11 record, changes in δ^{13}C values lead changes in δ^{18}O values by up to 7000 years (T. B. Coplen *et al.*, in preparation). Since the Devils Hole paleotemperature record similarly leads the SPECMAP record, then is it not a global precursor of this marine record? But, if so, why are the DH-11 and SPECMAP records apparently synchronous between 110 to 60 ka (Fig. 4)? Clearly, until the SPECMAP and Vostok record are well dated we will be unable to answer these questions, nor to address how these precursor parameters (SST, CO_2 levels, δ^{13}C values, and others) in different records relate to one another, to the three δ^{18}O time series, and to suspected primary climate forcing mechanisms. In the interim, the DH-11 record—by virtue of its detailed chronology—provides the most reliable information available on the timing and duration (but not the magnitude) of major global climatic events of the mid-to-late Pleistocene.
18. W. F. Ruddimann and H. E. Wright, Jr., in *North America and Adjacent Oceans During the Last Deglaciation*, vol. K-3 of the *Geology of North America*, W. F. Ruddiman and H. E. Wright, Jr., Eds. (Geological Society of America, Boulder, CO, 1987), pp. 1–12; A. Berger, *Quat. Int.* **2**, 1 (1989); *Rev. Geophys.* **26**, 624 (1988); J. Imbrie, in *Abrupt Climate Change*, W. H. Berger and L. D. Labeyrie, Eds. (Reidel, Boston, 1987), pp. 365–368.
19. M. Stein, *et al.*, in *Proc. Seventh Conf. Geochronology, Cosmochronology*, and *Isotope Geology*, Canberra, Australia, September 1990 (Geological Society of Australia, Canberra, 1990). Three of the seven mass-spectrometric U-series dates, with initial ^{234}U/^{238}U ratios indistinguishable from that of modern sea water, cluster about 135 ka; the remaining four dates cluster around 119 ka.
20. J. H. Chen, H. A. Curran, B. White, G. J. Wassenberg, *Geol. Soc. Am. Bull.* **103**, 82 (1991). Recent work has shown the need for extreme care in the U-series dating of corals used to reconstruct Pleistocene sea levels, as even apparently well-preserved specimens may not behave as closed systems for U-Th isotopes (see also T. L. Ku, M. Ivanovich, S. Luo, *Quat. Res.* **33**, 129, 1990; B. Hamelin, E. Bard, A. Zindler, R. G. Fairbanks, *Earth Planet. Sci. Lett.* **106**, 169 (1991). Although corals older than 100,000 years are especially at risk for such open-system behavior, dating for two sea-level studies [(*19*) and Chen *et al.*] passed criteria of acceptability far in excess of almost all earlier studies.
21. R. G. Fairbanks, *Paleoceanography* **5**, 937 (1990). His Fig. 2 shows that at 6 ka sea level was still 10 m below modern levels. Thus, conservatively, it took at least 13,000 years for sea level to rise from its full-glacial minimum of 120 m (at 19 ka) to modern levels.
22. A. Berger and P. Pestiaux, in *Milankovitch and Climate*, A. Berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman, Eds. (Reidel, Boston, 1984), part 1, pp. 83–111; A. L. Berger, *Quat. Res.* **9**, 139 (1978). The insolation curves of Figs. 3 and 4 were generated by a digitizing computer package scan of Fig. 2 in Berger and Pestiaux, and from an IBM-compatible diskette available from National Geophysical Data Center, 325 Broadway, E/GC Department 853, Boulder, CO 80303. Subsequent to preparation of Figs. 3 and 4, A. Berger and M. F. Loutre [*Quat. Sci. Rev.* **10**, 297 (1991)] released updated insolation computations; differences between their new data and our curves are negligible.
23. Recent attempts to model the period from 350 to 450 ka using nonlinear dynamical models have been unsuccessful [G. Matteucci, *Clim. Dynam.* **6**, 67 (1991); N. G. Pisias, A. C. Mix, R. Zahn, *Paleoceanography* **5**, 147 (1990)].
24. J. M. Landwehr, in preparation. Spectral analysis indicates robust δ^{18}O peaks (in order of decreasing power) of 93,000-, 40,000-, 25,000-, 23,000-, and 17,000-year cycles.
25. J. E. Joyce, L. R. C. Tjalsma, J. M. Prutzman, *Paleoceanography* **5**, 507 (1990); T. C. Moore, N. G. Pisias, and D. A. Dunn, *Mar. Geol.* **46**, 217 (1982); P. E. Olsen, *Science* **234**, 842 (1986).
26. J. Mangerud, in *Quaternary Landscapes*, L. C. K. Shane and G. J. Cushing, Eds. (Univ. of Minnesota Press, Minneapolis, 1991), pp. 38–75.
27. K. Lambeck and M. Nakada, *Nature* **357**, 125 (1992).
28. CLIMAP Project Members, *Quat. Res.* **21**, 123 (1984).
29. Current United States policy requires isolation of high-level radioactive wastes from the biosphere for at least 10,000 years after their emplacement in a repository [National Research Council, *Rethinking High-Level Radioactive Waste Disposal* (National Academy Press, Washington, DC, 1990)]. Consequently, on the widely accepted assumption that the Holocene is about over, considerable research is under way to determine the effects of pending glacial climates on proposed waste repositories [______, *Ground Water at Yucca Mountain: How High Can It Rise?* (National Academy Press, Washington, DC, 1992); C. M. Goodess, J. P. Palutikof, T. D. Davies, *Clim. Change* **16**, 115 (1990)]. However, if it were thought that the present interglacial would last another 10,000 years, then a reordering of research priorities, giving equal weight to studies of anthropogenic modification of Holocene climates and to early-glacial climates, might be considered. On a much shorter time frame, that is over the next several centuries, possible greenhouse warming will not necessarily be offset by cooling associated with the onset of a glacial cycle.
30. B. Saltzman, *Clim. Dynam.* **5**, 67 (1990).
31. Because the DH-11 record does not extend forward to termination I, we used the value 12 ka (taken from the SPECMAP and Vostok curves, Fig. 3) to arrive at our number of 128,000 years between terminations II and I. Between 110 and 60 ka, the DH-11, Vostok, and SPECMAP records are essentially synchronous (Fig. 3) and presumably would have remained so until the Holocene had calcite precipitation in vein sample DH-11 not ceased at 60 ka. Support for this belief comes from vein sample DH-7, collected in another portion of Devils Hole cavern. An alpha-spectrometric ^{230}Th date for the outermost few millimeters of this sample is 24 ± 1 ka, and the δ^{18}O values for this interval indicate full glacial climate.
32. P. Yiou *et al.*, *J. Geophys. Res.* **96**, 20, 365 (1991); H. LeTreut and M. Ghil, *ibid.* **88**, 5167 (1983); M. Ghil, in *The Sun in Time*, C. P. Sonett, M. S. Giampapa, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, 1991), pp. 511–542.
33. I. J. Winograd and W. Thordarson, *U.S. Geol. Surv. Prof. Pap. 712-C* (1975).
34. Vienna Standard Mean Ocean Water (VSMOW); Standard Light Antarctic Precipitation (SLAP); T. B. Coplen, *Chem. Geol.* **72**, 293 (1988). $\delta^{18}O = [(^{18}O/^{16}O_s - {}^{18}O/^{16}O_{VSMOW})/(^{18}O/^{16}O_{VSMOW})] \times 1000$, where s is the sample.
35. J. Imbrie *et al.*, in *Milankovitch and Climate*, A. Berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman, Eds. (Reidel, Boston, 1984), part 1, pp. 269–305. Data in their table 7 was used to construct curves in Figs. 3 and 4.

36. We thank R. J. Hoffman for assistance in the SCUBA retrieval of core DH-11. J. Anderson assisted in the preparation of Figs. 1 to 3 and in data processing. The National Park Service and the U.S. Fish and Wildlife Service granted us access to Devils Hole. We thank L. A. Bricker for thoughtful secretarial assistance. The manuscript was measurably improved by review comments of E. T. Sundquist, J. M. Thomas, and two reviewers.