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

Isaac J. Winograd, Tyler B. Coplen, Jurate M. Landwehr, Alan C. Riggs, Kenneth R. Ludwig, Barney J. Szabo, Peter T. Kolesar, Kinga M. Revesz

Oxygen-18 ($^{18}$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 $^{18}$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 (2).

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 mamillary 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 $^{18}$O and carbon-13 ($^{13}$C). The $^{18}$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 $^{18}$O (Fig. 2). The sampling interval (1.26 mm) represents an average time interval of about 1800 years.

The Devils Hole $^{18}$O-time curve (Fig. 2) clearly displays the sawtooth pattern characteristic of marine $^{18}$O records that have been interpreted to be the result of the waxing and waning of the Northern Hemisphere ice sheets during the Pleistocene (8). But what caused the $^{18}$O variations in DH-11 shown on Fig. 2? As discussed in (5), the $^{18}$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, Pahanagat Valley (and tributary areas) and possibly the Sheep
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 δ18O values of directly

**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 δ18O 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 δ18O values (14); however, a normalized plot of Vostok δ18O 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 δ18O values of planktonic foraminifera. It is indirectly dated by “tuning”;

**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 surface.

**Fig. 2.** Variations in δ18O values along 36-cm-long core DH-11. Each dot represents a calcite sample analyzed for δ18O values; ages were assigned to the δ18O 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 δ18O data (1σ) is 0.07 per mil, reported relative to VSMOW on a scale normalized to δ18O 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 interscal 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 δ18O 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 SPEC-

MAP record, this termination is subdued and amounts to a shift of only two standard deviations in δ18O, which is about half that of terminations I, II, IV, or V. In the DH-11 record, in contrast, termination III is bold, and δ18O 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 δ18O curve.

Sarnthein and Tiedemann (15) presented high-resolution planktonic and benthic δ18O 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 δ18O records.

The overall similarity of the DH-11 record to the SPECMAP record, to other equally detailed marine δ18O 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 8δO records, Antarctica ice sheet 8D 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 Dornk (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).

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The 100,000-Year Cycle and Implications

Much has been written about the origin of the dominant 100,000-year cycle present in mid-late Pleistocene isotope 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 δ¹⁸O 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-living 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 dynamists that Pleistocene climate phenomena are aperiodic and therefore that their timing is probably unpredictable (32).

In summary, the DH-11 δ¹⁸O paleoclimate record—anchored by 21 MSU 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.

REFERENCES AND NOTES


4. The nontectonic, hydrologic, and geochronal setting of this cave is discussed by A. C. Rigs, T. P. Coles and R. J. Hoffman, in preparation.


6. Core DH-11, as remeasured 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. The usable 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 axes approximately at an angle of 45°. Smaller, closely packed crystals of calcite with a complex internal structure in which many smaller (2 to 4 mm long and 0.25 to 1 mm wide) crystals are arranged like closely spaced tetrahedra from a common core. The smaller crystals are not understood (P. M. Grootes, in paper presented at the Chapman Conference of Continental Iso- tope Indicators of Climate, Jackson Hole, WY, 10 to 14 June 1991. Even so, an empirical relation between δ¹⁸O values in precipitation and temper- ature is well-documented globally for mid-to- high latitudes (See for example: Y. Yuvetse and F. P. Bar, Isot. Tech. Rep. 120681; J. Jouzel et al., Geophys. Res. 92, 14,739 (1987); D. A. Fisher, Am. Glaciol. 4, 165, (1990); S. J. Johnson, W. D. Dansgaard, J. W. C. White, Tellus 41, 452 (1989)). This empirical relation has also been documented for mid-latitude North American ground waters by C. J. Yonge et al. (Ches. Geol. 68, 397 (1989)), who report that the δ¹⁸O values of cave-seep waters with cave temperatures; they obtained virtually the same relation obtained by Yuvetse and Gat for pre- cipitation.

7. J. M. Thomas and M. D. Dettinger, manuscript in review.

8. Evidence suggesting that ground-water resi- dence times could be as small as 50 years, inferred from ¹³C dating includes: (1) Several dozen ¹³C-dated water samples from wells and springs around the Spring Mountains show no relation of either δ¹³C or δ¹⁸O with age for the past 20,000 years (11). These data can mean either that: (i) there was no variation in stable isotopic content with time; or (ii) there was a clear and unambiguous relationship that was not discerned by the Devils Hole and other records from the southwestern United States (5); (ii) the δ¹³C ages are correct, but Holocene climates were achieved before the widely accepted time frame of 10 to 12 ka; or (iii) the δ¹³C 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 resi- dence times derived from hydrogeologic data are consistent with the water management and used by the people of the region. This suggests that the δ¹³C curve is synchronous (with a few thousand years) with the Vostok ¹⁸O age to 150 ka and with the marine SPECMAP age for ages younger than 110 ka (Figs. 3 and 4); similarly, DH-11 δ¹⁸O data agree closely with sea-level stands as early as 136 ka (Fig. 4). (3) In view of the known hydrologic heterogeneity of Devils Hole and the wide spread precipitation of calcite from the slightly supersaturated waters.


9. Since publication of (5), we have obtained evi- dence that changes in ground-water temperature in Devils Hole did not affect by changing oxygen isotope fractionation between CaCO₃ and H₂O the δ¹⁸O value in the vein calcite. One of us (K.M.R.) analyzed the deuterium (D) in fluid inclusions of vein calcite. The long axes of the crystals introduced from the land-surface environment or organic compounds generated by the aquatic flora and fauna that colonized the newly available habitats. Alternatively, it is possible that the wide spread precipitation of calcite from the slightly supersaturated waters.


11. Since publication of (5), we have obtained evi- dence that changes in ground-water temperature in Devils Hole did not affect by changing oxygen isotope fractionation between CaCO₃ and H₂O the δ¹⁸O value in the vein calcite. One of us (K.M.R.) analyzed the deuterium (D) in fluid inclusions of vein calcite. The long axes of the crystals introduced from the land-surface environment or organic compounds generated by the aquatic flora and fauna that colonized the newly available habitats. Alternatively, it is possible that the wide spread precipitation of calcite from the slightly supersaturated waters.
14. C. Lorius et al. [Nature 391 (1998); Jouzel et al., ibid. 329, 403 (1987)]. The 3D curves in Figs. 3 and 4 were taken from Fig. 1 of Jouzel et al. [1987]. R. Petit et al. [Naturu 343, 56, (1990)] assigned an alternate chronology to the Vostok stable isotope time series than that used by the cited workers. They identified and tenta-
tively correlated full-glacial 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 chronolo-
gy to Vostok, resulting, for example, in 128 ka age for termination II. Petit et al. noted that their revision of the Vostok chronology was independent of absolute dating. Both chronologies con-
tinued to be used (3). Until the revision of the Vostok chronology, used in this paper, is probably more correct is indicated by its correspondence both to the DH-11 record and to MS uni-carbonium ages for sea ice. An alternate chronology, however, could still be valid for some times before 115 ka.
17. Unlike the SPECMAP record, the DH-11 record is not physically correlated to a globally averaged phenomenon such as the little ice age (13). Hence, the DH-11 record may reflect local or regional rather than global paleotemperature. We conclude that a local component existed first, because the MS uni-carbonium-series dates of sea ice for the period 135 to 119 ka correlate well with the warmest interval in the DH-11 record (see below and Fig. 4). We also note that the Devils Hole record to global ice volume; this correspondence also justifies our use of the global meaning (for the remainder of this paper). In this case, we use the term ‘terminations’ when discussing the DH-11 record. Second, the 135 to 119 ka time period 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: Does a purported local or regional record precede the global marine record? Two possibilities come to mind. We sug-
gest that the DH-11 record may be in error for ages older than 110 ka. Accordingly, we leave open the possibility that when the SPECMAP record is dated, the climatic events in the marine record must be seen to lead related temperature shifts in DH-11. Such a lead by the SPECMAP record might support Kutzbach’s suggestion that the climate of the South-
west 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. Ruddiman and H. E. Wright, Eds. (Geological Society of America, Boulder, CO, 1987), pp. 425–440). 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) varia-
tions in the Southern Hemisphere lead variations in marine-carbon-13 values by several thousand years of years (13), whereas CO2 and temperature varia-
tions in the Vostok core apparently lead marine-carbon-13 changes by at least 40,000 years (T. F. Sowers, M. Bender, D. Raynaud, Y. S. Korekovich, J. Orchoado, Paleoecology 6, 679 (1991)]. And, in the DH-11 record, changes in 81C values lead changes in 818O values by up to 7000 years (T. B.