

# Collapse of the California Current During Glacial Maxima Linked to Climate Change on Land

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Time series of alkenone unsaturation indices gathered along the California margin reveal large (4° to 8°C) glacial-interglacial changes in sea surface temperature (SST) over the past 550,000 years. Interglacial times with SSTs equal to or exceeding that of the Holocene contain peak abundances in the pollen of redwood, the distinctive component of the temperate rainforest of the north-west coast of California. In the region now dominated by the California Current, SSTs warmed 10,000 to 15,000 years in advance of deglaciation at each of the past five glacial maxima. SSTs did not rise in advance of deglaciation south of the modern California Current front. Glacial warming along the California margin therefore is a regional signal of the weakening of the California Current during times when large ice sheets reorganized wind systems over the North Pacific. Both the timing and magnitude of the SST estimates suggest that the Devils Hole (Nevada) calcite record represents regional but not global paleotemperatures, and hence does not pose a fundamental challenge to the orbital ("Milankovitch") theory of the Ice Ages.

One of the tasks of paleoclimatic studies is to better understand the linkages among different parts of the climate system that transport heat, determine the radiative properties of Earth's surface and atmosphere, or otherwise feed back into climate change. The ice volume cycles of the late Quaternary are recorded most faithfully and continuously in benthic oxygen isotope ( $\delta^{18}\text{O}$ ) records from marine sediments (1). Many other records are indirectly correlated to the benthic  $\delta^{18}\text{O}$  record on the basis of the strong similarity of their appearance to the ice volume (sea level) curve. Such correlations may often be correct, but they neglect the possibility of a regional fabric to how variables such as surface temperature, precipitation, and winds respond to the global ice age cycle. We undertook a study to relate past ocean surface temperatures along the California margin to global ice volume and regional terrestrial paleoclimatic variations. Our results suggest the existence of a set of regional feedbacks that

cause marine and nearby terrestrial temperature patterns to diverge from global ice volume during glacial maxima.

The present California Current system is intimately linked with atmospheric pressure systems over the North Pacific and western North America (2, 3). Cool, relatively fresh waters of the California Current system flow equatorward from the Oregon coast to just south of the U.S.-Mexico border, driven by prevailing winds (Fig. 1). Conditions favorable for coastal upwelling exist over much of the year, particularly in the summer months off northern California. About 1000 km offshore are the warmer, more saline, more oligotrophic waters of the central Pacific gyre. The dry Mediterranean climate of the adjacent coast of California directly reflects the present California Current system. More generally, much of the arid southwestern United States responds to the atmospheric conditions that drive the near-surface ocean along the California margin. When this system is disrupted, as in many El Niño years, sea surface temperatures (SSTs) increase along the California margin, upwelling diminishes (4), and rainfall becomes more frequent on land (5).

Marine sediment cores that span several full glacial cycles along much of the central western margin of North America have recently become available (Fig. 1 and Table 1). These sediments had high accumulation rates [generally >8 cm per 1000 years (ky)]. With one exception (the RGS0487 box and gravity core off southern Baja California), all cores have benthic  $\delta^{18}\text{O}$  data that provide the chronology for SST and

pollen changes. Because many of the core records extend through several glacial-interglacial transitions (terminations), they allow us to test whether patterns we observe since the peak of the last Ice Age some 21 ky ago (ka) are typical of the climatic response of the western margin of North America to late Pleistocene ice volume cycles. We estimate SST by applying a standard calibration (6, 7) to the alkenone unsaturation index in sediments, which proves an excellent proxy for mean annual SST along the California margin today (8). The alkenone proxy can be measured rapidly and is unaffected by carbonate dissolution, a common phenomenon in California margin sediments (9) that degrades SST estimates produced by microfossil assemblage techniques.

Individual benthic  $\delta^{18}\text{O}$  records were correlated to a master chronological model produced by tuning the marine record over the past 400 ka to precessional variations in the  $\delta^{18}\text{O}$  of air in polar ice cores (10) and to an ice volume model with a specific blend of eccentricity, obliquity, and precessional orbital forcing (11) for the earlier part of our records. The absolute error of the orbital age model (in its own terms) is estimated at  $\pm 5$  ky (12). We tuned to the most distinctive features of the isotope records, on average about 20 ky apart. The Devils Hole isotopic record discussed later has been radiometrically dated to errors of a few ky at 22 points over a 500-ky interval (13, 14). However, because many oxygen isotopic determinations from the Devils Hole record fall between dated intervals, the chronology for the calcite vein contains interpolation error in addition to the above-mentioned analytical error. The reader should thus bear in mind that discrepancies in estimated age on the order of 3 to 8 ky between the Devils Hole and nearby marine records are to be expected.

**Systematic regional sea surface temperature responses to ice age cycles.** Alkenone paleotemperature data document high amplitude variations in SST along the California margin across five full ice age cycles (Fig. 2) (15). Ocean Drilling Program (ODP) site 1020 represents conditions in the northern limb of the California Current. Sites 893, 1012, and EW03 reflect conditions in the California Borderlands near the present southern front of the California Current system, whereas the LPAZ core records SST variations in a region dominated by subtropical waters. The total amplitude of glacial-interglacial change in SST was nearly 10°C off northern California, 8° to 9°C in the borderland region, and 4°C off Baja California. Waters along southern California were frequently as cold as present-day conditions off the southern Oregon coast, whereas waters as warm as those now at Santa Barbara occurred along the Oregon margin during some previous interglacial periods. Surface temperatures as low as 5°C at site 1020 presumably coincide with ice-rafting in the North Pacific, which

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penetrated from the north to within 5° latitude of the site during glacial periods (16, 17) and with the southward migration of the glacial polar front deduced from sediment cores in the North Pacific (18).

As Fig. 2 shows, the coldest temperatures recorded along the California margin generally did not coincide with maximum ice volume (registered by benthic  $\delta^{18}\text{O}$  data). We retain the usual definition of glacial maxima as periods of maximally enriched  $\delta^{18}\text{O}$  values, lasting for several thousand years in each glacial cycle, as distinct from time periods of minimum surface temperature. Maximum cooling by this definition precedes glacial maxima by 5 to 10 ky in each glacial cycle. At the northern end of the core transect, the alkenone estimate of cooling at the Last Glacial Maximum (LGM), 4°C, is similar to those obtained from a nearby core from radiolarian and foraminiferal transfer function estimates (19, 20), planktonic  $\delta^{18}\text{O}$  (20), and alkenone unsaturation (21). The

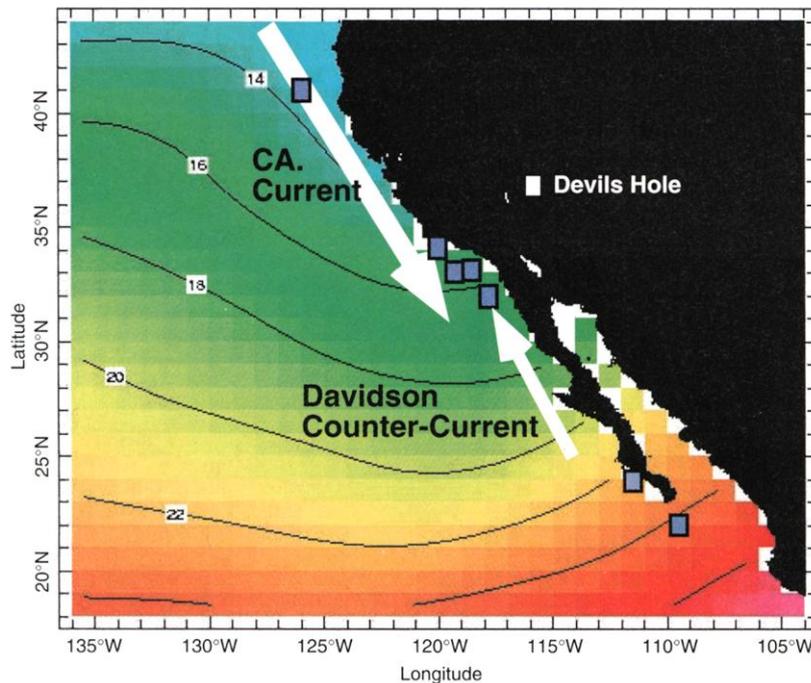
smaller amount of cooling (1° to 2°C) at the LGM in the borderland region agrees with previous alkenone results (22) and radiolarian estimates (19) but not with foraminiferal data (23, 24). We choose the alkenone estimates because the proxy has been well calibrated along the California margin in surficial sediments, because it is unambiguously related to near SSTs, and because it is insensitive to the changes in preservation that greatly affect foraminiferal faunas in cores from the region.

Two systematic relations between SST and ice volume seem to hold across multiple repetitions of the late Quaternary ice age cycles along the California margin. The first is the tight correspondence of SST and ice volume in interglacial and early glacial phases of climate. For example, SST changed in unison with benthic  $\delta^{18}\text{O}$  from the peak of marine oxygen isotope stage 5e (123 ka) through oxygen isotope stage 4 in the last glacial cycle. In each record, the previous interglacial (isotope stage

5e) produced surface waters several degrees warmer than today.

However, temperature and ice volume the California Current region depart notably during glacial maxima and early deglacial conditions. These are indicated in Fig. 2 by rises in SST that begin before maximum oxygen isotopic enrichment (indicated by vertical bars). Because oxygen isotope and alkenone data were acquired from the same cores, the offset cannot be an artifact of correlation. The precise time offset depends on the age model used, but the reader should note that the anomalies indicated by arrows in Fig. 2 are defined by a number of measurements and occur at similar positions relative to oxygen isotopic stratigraphy at each study location (for example, SST rises at all sites at the midpoint of isotopic stage 6.3, well in advance of termination II). Multiple realizations of ice age cycles allow us to rule out the possibility that the early warming observed in the California Current region at the LGM is fortuitous. Early deglacial warmings are characteristic of nearly every glacial termination; the warming observed before the end of the last Ice Age is a consistent response that must testify to a predictable set of physical responses to maximum ice volume and subsequent ice sheet decay. Warming began about 12 ky, on average, before the steep rise in sea level characteristic of terminations. Thus, SST along the California margin increased after about 26 ka in the most recent glacial cycle, whereas global sea level rose rapidly beginning at about 15 ka (25). Temperature leads of similar duration occur at earlier glacial maxima.

The absence of early warming south of the California Current region (LPAZ core in Fig. 2 as well as the RGS0487 cores listed in Table 1) links the anomalous SST response to the dynamics of the regional wind system during glacial maxima. We argue that the glacial-interglacial response of SST along the California margin comes from two distinct scales of atmospheric and oceanic variability. For most of the record, SST marches tightly with the oxygen isotopic proxy for sea level and with high-latitude Northern Hemisphere orbital forcing. Thus, for the first 80 to 90 ky of a typical interglacial-glacial 100-ky cycle, the pattern of SST in the eastern North Pacific would resemble that in the North Atlantic and would reflect hemisphere-wide changes in heat transport as well as  $\text{CO}_2$  and ice-albedo feedbacks. However, beginning some 5 ky before maximum glaciation, a more regional set of processes causes SST to diverge from patterns characteristic of other regions. The early temperature rise is modest to the north (ODP site 1020) and absent off central Baja (Fig. 3). This pattern, we believe, is diagnostic of a substantial weakening of the California Current at glacial maxima. The largest positive SST anomaly (relative to ice volume) occurs at the southern margin of the present California Current. If the California



**Fig. 1.** Mean annual SST along the California margin. Major surface currents are schematically represented by white arrows. Marine core locations discussed here are indicated by blue boxes (see Table 1 for coordinates). The Devils Hole location provides a continental record of  $\delta^{18}\text{O}$  variations in vein calcite.

**Table 1.** Core locations.

Site	Latitude	Longitude	Water depth (m)
ODP 1020	41°N0.03	126°W26.04	3038
ODP 893	34°N17.25	120°W02.2	575
ODP 1012	32°N16.97	118°W23.02	1772
EW9504-09PC	32°N51.51	119°W57.48	1194
EW9504-03PC	32°N04.38	117°W21.95	1245
EW9504-02PC	31°N15.52	117°W35.14	1298
RGS0487 BC9/GC11	23°N41	111°W05	381
RGS BC41/GC44	23°N54	111°W44	265
LPAZ 21P	22°N59.4	109°W28.0	624

Current were to weaken substantially, warm gyre waters would penetrate toward the coast. Such a reduction in southerly transport of cold surface water would have the largest impact on SST in the boundary region of the California Current, explaining the large warm anomalies in cores from the Borderlands region. Waters off Baja California, which are well south of the California Current, did not experience an early warming, while to the north, in the core region of the Current, the equatorward flow of water was sufficient to prevent warm gyre waters from impinging on the margin as strongly as in the borderland region.

We infer that a critical size of the North American ice sheet strongly perturbed the wind system, which today drives cold waters equatorward along the California margin. Modeling studies (26, 27) indicate that the Laurentide ice sheet had a strong influence on atmospheric circulation over North America at the LGM. In particular, winds reconstructed along the western margin for the last glacial period did not favor the eastern boundary current. This pattern is consistent with our inference that the central Pacific gyre encroached onto the California margin to produce warm anomalies during glacial maxima and terminations. Further support for the glacial reduction in California Current transport comes from the lower organic carbon and Ba mass flux (28), decreased marine biomarker content (29, 30), and altered diatom assemblages (30), all testifying to less favorable atmospheric forcing of upwelling and productivity along the California margin. At the same time, pluvial conditions in the Great Basin lakes indicate that atmospheric pressure cells moved substantially from the present configuration (31). Ice sheet feedbacks were therefore strong enough to quell one of the major eastern boundary current systems operating today, and to reorient storm tracks in southwestern North America.

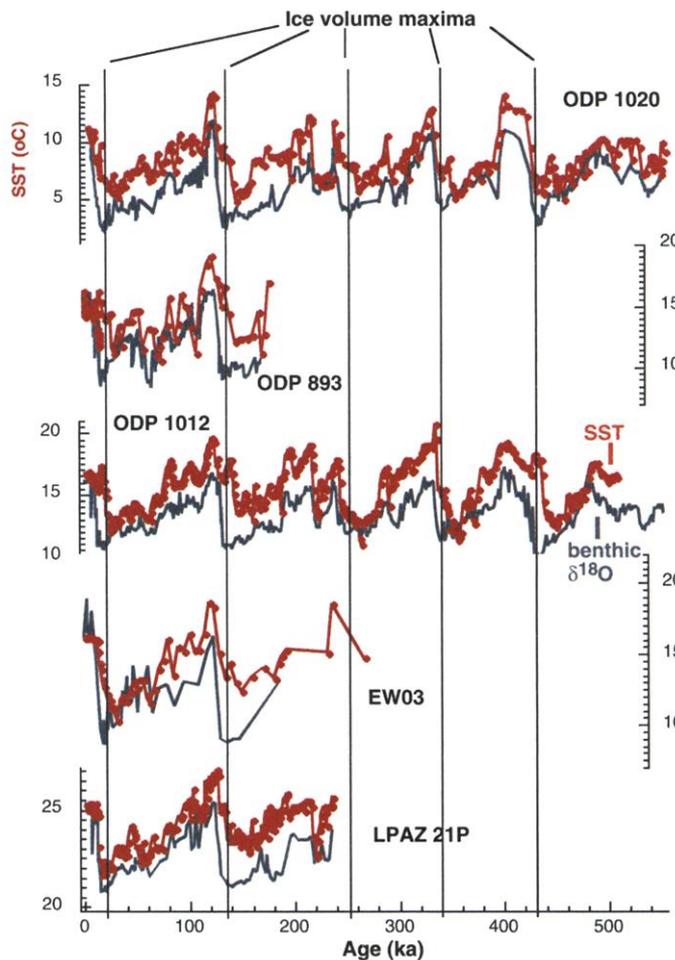
The early warming of the California margin conflicts with the general notion that global temperatures were coldest at glacial maxima. The patterns we document differ substantially from faunal (32) and alkenone (33) temperature time series from the North Atlantic, where temperatures follow the classic "sawtooth" pattern of sea level, rising steeply at terminations. However, Ruddiman and McIntyre's study (32) clearly shows regional variations in temperature response between tropical and northern sites in the Atlantic, and Crowley (34) contended that SST rose well before sea level in the subtropical (25°N, 44°W) North Atlantic. Alkenone time series in the eastern tropical Atlantic Ocean also display an early glacial-deglacial rise in SST, particularly at the oxygen isotope stage 5–stage 6 transition (35). Recent Mg/Ca estimates of paleotemperatures in the equatorial Pacific show that SST rose early relative to deglaciation, although the ~3-ky lead (36) is substantially shorter than in the California Current

region. Similar to the California margin data, temperatures warmer than the Holocene are recorded in the equatorial Pacific for isotope stages 5e and 11.

**Relation of California margin marine temperatures to coastal vegetation.** Analysis of pollen preserved in continental margin sediments ties changes in vegetation in the Pacific coastal zone to nearby changes in SST and global ice volume (37–39). These studies and a new factor analysis of pollen variations at ODP site 1020 show strong relationships between changes in ocean conditions offshore and changes in vegetation on land. A three-factor varimax model explains 96% of the pollen variance (40). Factor 3 (27% of variance), dominated by positive loadings of *Sequoia*, *Quercus*, and *Alnus*, was recognized qualitatively in a previous study of the pollen content at ODP site 1020 (37). Figure 4 demonstrates the tight relation of this vegetative assemblage to variations in SST recorded by the alkenone index at site 1020. We also display the down-core record of the abundance of *Sequoia*, a key component of factor 3. Factor 3 represents species adapted to the interglacial conditions of the modern northern California coast. *Sequoia* in particular requires mild temperatures and the fog produced by coastal upwelling to thrive (37). Redwoods

reached abundances greater than 2% only when marine temperatures rose above about 9°C. The factor 3 time series demonstrates a very good correlation not only in the timing of maxima and minima to SST, but in the amplitude of the glacial-interglacial variability (for example, unusually warm SSTs at isotope stages 5.5 and 11 coincide with the highest factor scores).

Because the pollen data come from the same material that provides the marine proxy data, there can be little stratigraphic uncertainty in inferring a tight correlation between marine temperatures and response of an important assemblage of coastal plants on the California margin. In detail, a rise in alder pollen at ODP site 1020 and at core Y7211 1 [slightly north (41)] coincides with the early warming (relative to glacial terminations) so characteristic of the California margin alkenone records, whereas the later peak in redwood abundance at thermal maxima may record the combination of both mild temperatures and coastal fog induced by active upwelling in the typical interglacial mode of the California Current. The delayed rise in *Sequoia* could indicate that the initial warming did not include upwelling and coastal fog. The association of oak and alder with warm, interglacial climates also occurs to the south in the Santa Barbara Basin record of ODP



**Fig. 2.** Synthesis of glacial-interglacial variations in alkenone SST, arrayed from north to south along the California margin. The time scales come from tuning benthic  $\delta^{18}\text{O}$  variations to the SPECMAP chronology. Vertical lines indicate the stratigraphic positions of glacial maxima; note the early warming of SST relative to ice volume at glacial terminations.

893 (42). Heusser (42) argued that *Quercus* appeared abruptly at the beginning of interglacial periods, and indeed there may be a later response of vegetation relative to the late glacial rise in SST in southern California. One can note, however, that minima in the abundance of *Quercus* precede the interval of lowest sea level

defined by benthic oxygen isotope data at site 893 by some 5 to 10 ky.

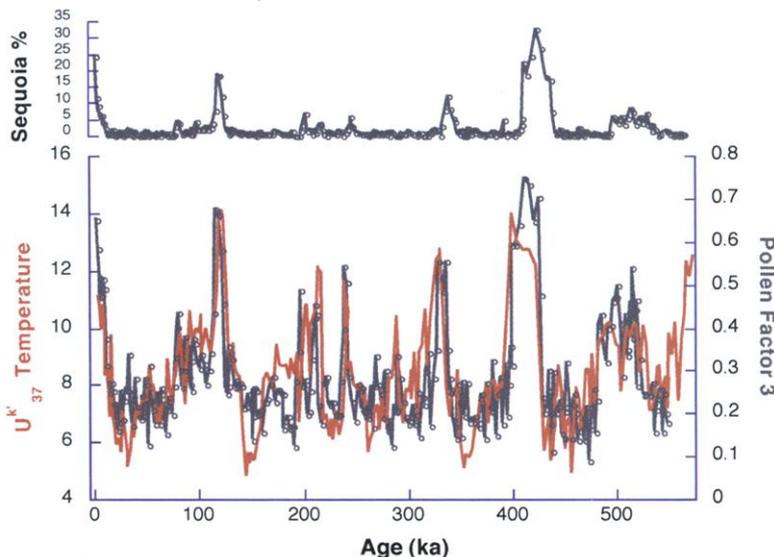
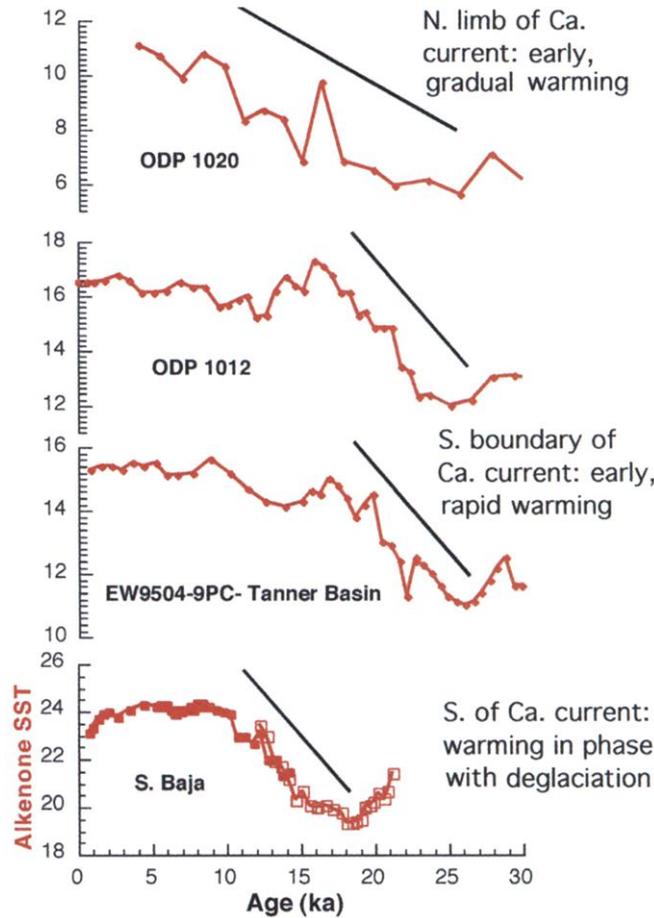
**Implications for the Devils Hole calcite record.** The correspondence between coastal vegetation changes and marine temperatures inferred from alkenone data led us to reexamine the ~550-ky isotopic record of vein calcite at

Devils Hole, Nevada (13), located ~325 km from the southern California coastline. The Devils Hole record provides an unusually well-dated (14) picture of terrestrial climate through isotopic changes in carbonate precipitated from ground waters. Rainfall today comes in the winter and spring months from a Pacific source (13), and we assume that most precipitation in the past has also come from the North Pacific. Winograd *et al.* inferred from the strong similarity of the vein calcite  $\delta^{18}\text{O}$  time series to the SPECMAP compilation of marine oxygen isotopes that Devils Hole offers a globally valid chronology of glacial-interglacial climate cycles. The early occurrence of isotopically heavy values at glacial terminations, relative to the SPECMAP chronology, was interpreted to pose a challenge to the orbital ("Milankovitch") theory of the Ice Ages, because the shifts occurred well before increases in Northern Hemisphere insolation. However, because the signs of the marine and Devils Hole  $\delta^{18}\text{O}$  changes are inverse (the Devils Hole record becomes isotopically heavy in interglacial periods when the marine record becomes light because of the addition of isotopically light glacial meltwater), the isotopic correlation must be indirect.

Factors that could change the  $\delta^{18}\text{O}$  composition at Devils Hole include surface air temperature [global relation of +0.6 per mil per  $^{\circ}\text{C}$  warming (43)]; groundwater temperature (inorganic calcite relation of about -0.2 per mil per  $^{\circ}\text{C}$  warming); global changes in the isotopic composition of marine source waters for continental precipitation [total glacial-interglacial amplitude of 1.0 to 1.2 per mil (44, 45)]; changes in kinetic isotopic fractionation in the marine source region with wind speed [perhaps +0.7 per mil during glacial periods (46)]; changes in the temperature of the marine source region (-0.1 per mil per  $^{\circ}\text{C}$  SST warming); and regional changes in the isotopic composition of the marine source region supplying rain to southwestern Nevada. The ~2 per mil amplitude of glacial-interglacial  $\delta^{18}\text{O}$  variations at Devils Hole must thus be parsed as some combination of the variables above, although Winograd and colleagues chose to interpret the record as a proxy for changes in surface temperature. Recent work by the Devils Hole group accepts that paleotemperature variations in Nevada resemble those of the nearby Pacific (47).

We believe that the early warmings (relative to an orbitally tuned glacial-interglacial chronology) observed in the Devils Hole record are entirely consistent with SST patterns along the California margin and should not be confused with the global ice volume signal. The correlation between offshore and terrestrial temperatures may come from a direct buffering of continental temperatures by the thermal inertia of continental margin waters, or from a linked response coordinated by large-scale reorganization of atmospheric pressure systems over the north Pacific and southwestern North America.

**Fig. 3.** Detail of the last glacial-interglacial transition, documenting the regional nature of the early warming anomaly. The anomaly is most apparent in the southern California region, is present but of smaller amplitude to the north, and is not present off Baja California. Chronology at sites 1012 and 1020 comes from benthic  $\delta^{18}\text{O}$  stratigraphy; chronology at sites EW9504-09 and RGS0487 BC9 comes from isotope stratigraphy and  $^{14}\text{C}$  accelerator mass spectrometry dating (50, 57).



**Fig. 4.** Correspondence between SST alkenone SST estimated at ODP site 1020 and the "warm" pollen assemblage determined from factor analysis.

Figure 5 displays the alkenone estimates of SST from ODP site 1012, on an oxygen isotopic time scale, in comparison to the Devils Hole record, dated by U-series methods. We have not attempted to tune the records to each other, which would improve the match further. Nevertheless, the coldest intervals of glacial stages in each record align well. In each of four terminations, the coldest conditions preceded the time of maximum ice volume (according to the standard SPECMAP age model) by some 20 ky. Because the alkenone estimates display this feature in direct comparison to benthic  $\delta^{18}\text{O}$  measurements, the age offset cannot be an artifact of errors in dating the marine oxygen isotope record. The timing of maxima and minima in both marine and terrestrial records shows a tight correspondence to the marine oxygen isotope record during interglacial stages; anomalous temperature variations occur only during maximum glaciation and terminations.

Substantial problems with either the benthic  $\delta^{18}\text{O}$  age model or the Devils Hole age model occur from oxygen isotope stage 12 through 13 (420 to 520 ka on the Devils Hole age scale). We believe that the warm interval dated at 455 ka at Devils Hole almost certainly matches the period of warm ocean temperatures dated at about 485 ka at both ODP sites 1012 and 1020. The Devils Hole chronology has tie points in the relevant interval at 438, 461, and 513 ka. If we accept these ages, the calculated calcite growth rate shows an anomalous association of high growth rate with cold, glacial conditions for ages greater than 440 ka (Fig. 5). All later glacial cycles show a good correlation between slower growth rate and cold temperatures. The high apparent growth rate (about double all other glacial intervals) compresses the Devils Hole isotopic features equivalent to oxygen isotope stages 12 and 13 relative to our marine SST record. Regression analysis indicates a sharp roll-off in the correlation coefficient between ODP 1012 and Devils Hole if data older than 420 ka (Devils Hole time scale) are included. It appears likely that the Devils Hole dates of 438 and 461 ka are too young by 10 to 20 ky. The detailed comparisons we make below therefore apply to what we believe is the well-dated interval at Devils Hole between 60 and 420 ka.

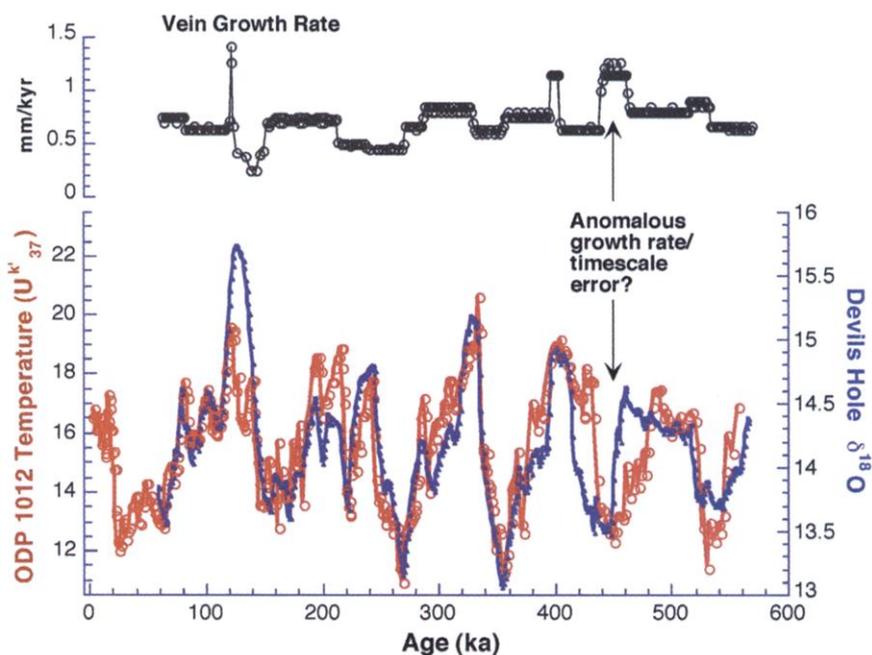
The correlation coefficient of +0.78 between marine surface temperatures at ODP site 1012 and the Devils Hole  $\delta^{18}\text{O}$  record is substantially better than the -0.5 reported between Devils Hole and the SPECMAP  $\delta^{18}\text{O}$  record (the correlation coefficient between ODP 1020 and Devils Hole is +0.7). Furthermore, there is a strong physical basis to correlate two nearby records best interpreted to reflect surface marine and terrestrial temperatures. Our regression produces a slope of about +0.2 per mil between the oxygen isotopic composition of Devils Hole calcite and a  $1^\circ\text{C}$  change in nearby marine surface temperatures. The glacial to interglacial SST amplitude of  $6^\circ$  to  $8^\circ\text{C}$  evidenced by alk-

enones would produce a range of 3.6 to 4.8 per mil in the  $\delta^{18}\text{O}$  of rainfall, if the Devils Hole region experienced the same temperature changes, and if the global relation of temperature to isotopic content of precipitation—around which there is considerable regional variance (43)—applies. Glacial enrichment in marine source waters, the inorganic temperature effect on  $\delta^{18}\text{O}$  of calcite if groundwater cooled somewhat during glacial periods at the Devils Hole site, and ocean cooling in the source region of water vapor would all damp this amplitude considerably, yielding a plausible match to the 0.2 per mil per  $^\circ\text{C}$  relation quoted above. Tuning the chronology of either marine or Devils Hole records could not remove amplitude mismatches most evident at about 120 to 140 ka and 190 to 220 ka. These presumably testify to changes in factors relating the isotopic composition of Devils Hole calcite to marine temperatures.

Early warming at Devils Hole relative to an orbital  $\delta^{18}\text{O}$  chronology appears to be entirely expected if our correlation of marine and terrestrial temperatures is correct. The timing of the warming (on average about 12 ka before rapid sea level rise) is very similar in both marine and terrestrial records through five glacial terminations, and, given the errors in both time scales, is likely synchronous.

**Conclusions.** The SPECMAP strategy of studying the regional progression of climatic responses relative to global changes in ice volume (1) anticipated the probability that not all glacial-interglacial climate change occurred in lock-step over the surface of Earth. The prob-

lem of nonsynchronous climatic change becomes particularly noteworthy when one compares records based largely on visual similarities, as is commonly done to link terrestrial and marine proxy data sets. Without doubt, large-scale features associated with the 100-ky glacial-interglacial cycle generally correlate. But as the chronological window contracts, an overly rigid perspective may misplace the timing of regional events diagnostic of the “wiring” of climatic feedbacks, unless the proxy time series can be directly correlated to the marine oxygen isotope record, or dated directly. The anomalous behavior of SST along the California margin relative to ice volume occurs only during peak glaciation, implying a set of feedbacks specific to a threshold size of the Northern Hemisphere ice sheets. Our study shows not only that a collapse of the California Current occurred at the last Ice Age, but also that it occurred in nearly identical mode in previous glacial maxima and their terminations. The perturbations to wind fields induced by the Laurentide ice sheets must therefore be quite predictable and amenable to modeling. We suggest that the Devils Hole calcite record faithfully records regional, but not global, climatic change [see also (34, 48)]. Because the “anomalous” marine and terrestrial temperatures come from regional-scale feedbacks associated with maximum glaciation, they do not pose a fundamental problem for Milankovitch theory. Other dated records that contain a substantial component of surface temperature change [e.g., the planktonic isotope record of (49)] should also



**Fig. 5.** Comparison of a representative alkenone record (ODP 1012) with the Devils Hole  $\delta^{18}\text{O}$  record, on independent time scales. The good match, in particular the rise in temperature and  $\delta^{18}\text{O}$  of both records before deglaciation, suggests that regional, not global, temperature changes dominate the isotopic composition of the terrestrial record. The growth rate of the Devils Hole vein inferred from the Devils Hole time scale contains an anomalous interval beginning at 438 ka, suggestive of a dating error.

be examined in a similar light before they can be unambiguously interpreted to constrain the absolute chronology of late Pleistocene sea level and ice volume change.

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- Sixteen pollen units were counted by L. Heusser, with the abundance of ferns tabulated as well. *Pinus* (pine) dominates the entire record, accounting for an average of 61% of the assemblage on a fern-free basis. Other significant components include *Picea* (spruce), *Tsuga heterophylla* (western hemlock), *Abies* (fir), inaperturate conifer types (juniper/cedar), *Sequoia* (redwood), *Quercus* (oak), *Alnus* (alder), *Compositae* (sunflower family), and family *Artemesia* (sage). We extracted statistical groupings of pollen that might reflect the changes in climate. A square root transform of pollen abundance reduced the dominance of *Pinus* and produced a more Gaussian distribution of factor scores in the resultant time series than a linear transform of pollen abundance (note that one would arrive at similar pollen factors and time series results with a linear transform as well). An analysis that excluded ferns produced three factors that account for 96% of the variance in the data. Factor 1 (42% of variance explained) contains high positive loadings of *Pinus*, *Picea*, *T. heterophylla*, and *Abies*. Negative loadings of *Pinus* and family *Artemesia* characterize factor 3 (28% of variance).
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## REPORTS

## Carbon Nanotube Single-Electron Transistors at Room Temperature

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Room-temperature single-electron transistors are realized within individual metallic single-wall carbon nanotube molecules. The devices feature a short (down to ~20 nanometers) nanotube section that is created by inducing local barriers into the tube with an atomic force microscope. Coulomb charging is observed at room temperature, with an addition energy of 120 millielectron volts, which substantially exceeds the thermal energy. At low temperatures, we resolve the quantum energy levels corresponding to the small island. We observe unconventional power-law dependencies in the measured transport properties for which we suggest a resonant tunneling Luttinger-liquid mechanism.

Single-electron transistors (SETs) have been proposed as a future alternative to conventional Si electronic components (1). However, most SETs operate at cryogenic temperatures, which

strongly limits their practical application. Some examples of SETs with room-temperature operation (RTSETs) have been realized with ultrasmall grains, but their properties are extreme-

ly hard to control (2–4). The use of conducting molecules with well-defined dimensions and properties would be a natural solution for RTSETs. We report RTSETs made within an individual metallic carbon nanotube molecule (5), characterizing their transport properties as a function of temperature, bias, and gate voltage and observing unexpected power-law characteristics that we describe with a Luttinger-liquid model.

SETs consist of a conducting island connected by tunnel barriers to two metallic leads (1). For temperatures and bias voltages that are low relative to a characteristic energy required to add an electron to the island, electrical transport through the device is blocked. Conduction

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