3) wire, chirality appears as a by-product of reconstruction (requiring a large number m = 7 of strands per tube) and of tight fitting of the central strand inside the tube, which requires that the radius $(m^2 + n^2 - mn)^{1/2}$ be minimized and thus that n be as high as possible (here, n = 3). It seems again likely that this mechanism could carry over to the thicker magic nanowires; because of high string tension, the wires with the largest n and with small R and large L values should again prevail. The largest n for odd m is (m - 1)/2, and this leads to chirality, in agreement with model structures presented for outer tubes with m = 11, 13, and 15 (3).

Experimental consequences of nanowire chirality should be interesting to pursue. Properties attributed to nanowire chirality were pointed out in (19) and (20). Direct calculation of the helical current density that is connected with each of the conducting channels of the (7, 3) wire, based on our wave functions, is possible. Whether the joint effect of all channels would be such as to yield a measurable inductance as in a kind of nanosolenoid (21) is an open question, presently under consideration.

References and Notes

- 1. Y. Kondo, K. Takayanagi, *Phys. Rev. Lett.* **79**, 3455 (1997).
- H. Ohnishi, Y. Kondo, K. Takayanagi, *Nature* **395**, 780 (1998).
- 3. Y. Kondo, K. Takayanagi, Science 289, 606 (2000).
- 4. V. Rodrigues, T. Fuhrer, D. Ugarte, *Phys. Rev. Lett.* **85**, 4124 (2000).
- 5. E. Tosatti, S. Prestipino, Science 289, 561 (2000).
- 6. O. Gülseren, F. Ercolessi, E. Tosatti, *Phys. Rev. Lett.* **80**, 3775 (1998).
- R. N. Barnett, U. Landman, *Nature* **387**, 788 (1997);
 U. Landman, *Phys. World* **11**, 18 (July 1998).
- 8. M. R. Soerensen, M. Brandbyge, K. W. Jacobsen, *Phys. Rev. B* 57, 3283 (1998).
- 9. O. Tomagnini, F. Ercolessi, E. Tosatti, *Surf. Sci.* 287/ 288, 1041 (1993); unpublished note.
- 10. G. Bilalbegovic, Solid State Commun. 115, 73 (2000).
- 11. J. A. Torres et al, Surf. Sci. 426, L441 (1999).
- N. Hamada, S. Sawada, A. Oshiyama, *Phys. Rev. Lett.* 68, 1579 (1992).
- 13. A. F. Voter, *Technical Report No. LA-UR-93-3901* (Los Alamos National Laboratory, Los Alamos, NM, 1987).
- Coordinates of the (7, 3) nanowire are available at www.sciencemag.org/cgi/content/full/291/5502/ 288/DC1.
- A. I. Yanson, I. K. Yanson, J. M. van Ruitenbeek, *Phys. Rev. Lett.* 84, 5832 (2000).
- 16. F. C. Frank, Proc. R. Soc. London Ser. A **215**, 43 (1952).
- 17. E. Tosatti, F. Ercolessi, Int. J. Mod. Phys. B 5, 413 (1991).
- N. Takeuchi, C. T. Chan, K. M. Ho, *Phys. Rev. B* 40, 1565 (1989).
- V. N. Bogomolov, Yu. A. Kuzmerov, V. P. Petranovskii, A. V. Fokin, *Kristallografiya* 35, 197 (1990).
- 20. T. G. Schaaff, R. L Whetten, J. Phys. Chem. B 104, 2630 (2000).
- 21. Y. Miyamoto, A. Rubio, S. G. Louie, M. L. Cohen, *Phys. Rev. B* 60, 13885 (1999).
- 22. In our density functional calculations, we used the local density approximation. Selected trials using a generalized gradient approximation (which we do not favor because it yields surface energies that are too low) gave similar results. For gold, we used plane waves and Vanderbilt ultrasoft pseudopotentials, as in work by A. Dal Corso et al. [Phys. Rev. B 56, R11369 (1997)], and for silver, we used self-generat-

ed pseudopotentials [local s potential and core radii (in bohr), respectively, for 4d (1.8 and 2.4 ultrasoft radius) and for 5p (2.5)] derived as in work by G. Kresse and J. Hafner [J. Phys. Condens. Matter 6, 8245 (1994)]. Kinetic energy cutoffs for wave functions and charge density is 25 and 200 rydbergs, respectively, for silver and gold. Spacing between one-dimensional k_2 points is 0.147 Å⁻¹ (k_2 is the wave vector along the wire axis). 23. We acknowledge discussions and help from F. Ercolessi, K. Takayanagi, G. Santoro, G. Scoles, J. A. Torres, and A. Delin and support from Ministero dell'Università e della Ricerca Scientifica e Tecnologica (Cofinanziamento '99 and "Iniziativa trasversale calcolo parallelo"), Training and Mobility of Researchers (FULPROP), and Istituto Nazionale di Fisica della Materia.

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Orbital Forcing of the Marine Isotope Stage 9 Interglacial

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Milankovitch orbital forcing theory has been used to assign time scales to many paleoclimate records. However, the validity of this theory remains uncertain, and independent sea-level chronologies used to test its applicability have been restricted largely to the past ~135,000 years. Here, we report U-series ages for coral reefs formed on Henderson Island during sea-level high-stands occurring at ~630,000 and ~330,000 years ago. These data are consistent with the hypothesis that interglacial climates are forced by Northern Hemisphere summer solar insolation centered at 65°N latitude, as predicted by Milankovitch theory.

Knowledge of the precise timing of past sealevel high-stands provides a crucial test of the Milankovitch model of climate change. This theory postulates that glacial-interglacial cycles are driven by periodic changes in July solar insolation at 65°N, caused by predictable variations in Earth's orbit (1). Previous U-series studies have focused almost exclusively on the last interglacial period, Marine Isotope Stage (MIS) 5.5, occurring at about 125,000 years ago (ka) (2-9). The timing of the MIS 5.5 sea-level high-stand appears consistent with Milankovitch forcing theory (8, 10). However, there is a growing body of evidence that factors other than 65°N summer solar insolation may have triggered the MIS 6-5 deglaciation, which appears to have begun before insolation started to increase (10-12). In contrast, the last deglaciation, which began at ~ 21 ka, can be adequately explained by 65°N insolation forcing alone. This raises the possibility that a different combination of forcing mechanisms may have operated during previous glacial-interglacial cycles (13).

To help resolve this apparent contradiction, the Milankovitch climate model can be tested by dating coral reefs that formed during older interglacials. However, it is exceedingly difficult to obtain reliable chronologic

*To whom correspondence should be addressed. Email: stirling@erdw.ethz.ch information for older sea-level high-stands because of a lack of well-preserved, datable coral.

Here, we report 30 precise U-series ages for a set of reef terraces formed during MIS 9 and MIS 15 on Henderson Island near Pitcairn Island in the equatorial Pacific (Fig. 1). These data, obtained using thermal ionization mass spectrometry (TIMS) (7) and multiplecollector ICP sector mass spectrometry (MC-ICPMS) (14-16), provide reliable and independent radiometric constraints on the global sea level curve at ~630 and ~330 ka.

Henderson Island is located in the extreme east of the Indo-Pacific subtropical province, resulting in severe restrictions in ecological development (17, 18). Therefore, coral terraces form only during exceptionally long (18) or warm interglacials. Offshore fringing reefs grew prolifically on Henderson Island during the MIS 9 interglacial, but no coral terraces appear to have formed subsequently during the MIS 7.1, MIS 5.5, or mid-Holocene sea-level high-stands.

Growth-position corals were collected from reef terraces along seven lyphenate cliff-section transects and one central fossil lagoon transect during the 1991–92 Pitcaim Islands Scientific Expedition (18, 19). U-series results for corals selected for dating are displayed in Web table 1 (16). In the 330 ka samples, ²³⁰Th-age uncertainties (excluding the systematic contribution from the decay constants) can be smaller than ± 2 ka, allowing the timing and duration of the MIS 9 interglacial to be well resolved. For completeness, all age uncertainties reported here include the decay constant contributions. Approximately one-third of the samples are

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considered to have acceptable ²³⁰Th-ages [Web table 1 (16)] (Fig. 2A) (20). This is a very large proportion, given the old age of the reefs. Even in MIS 5.5 samples, it is not unusual to reject more than half of the data on the basis of selection criteria for reliability (5, 9). Acceptable ages range between 334 ± 4 and 293 ± 5 ka. Three reliable samples were measured in duplicate, and the ²³⁰Th-ages are concordant [Web fig. 1 (16)], despite the expected heterogeneity in U-Th isotopic composition resulting from enhanced diagenesis in some parts of the coral skeleton over others. Even samples that do not pass reliability criteria show a high degree of consistency within a sampling transect: the highest levels of diagenesis appear to have occurred along Transect 3 and in the fossil lagoon, as indicated by very elevated $\delta^{234}U(T)$ [a proxy for the U isotopic composition of the seawater in which the coral formed; Web table 1 (16)] in all samples.

Reefs also grew on Henderson Island during a major atoll construction phase occurring near 630 ka. Because MC-ICPMS can routinely achieve sub-permil analytical uncertainties for both U and Th measurements, U-series chronology can be extended beyond the 500 ka upper limit usually reported for TIMS. Two samples recovered from the fossil lagoon in the interior of the island (Fig. 1) have statistically identical ²³⁰Th-ages of 642 +36/-32 ka and 628 ± 25 ka (weighted mean of three results), and probably record the earliest emergent reef growth on Henderson Island. The weighted mean result of 632 ± 21 ka provides a direct U-series constraint on the timing of the MIS 15 interglacial sea-level high-stand.

Despite their old age, the Henderson Island "330 ka" coral terraces are exceptionally well preserved (21). Some diagenetic alteration has occurred, but the effect on the 238 U- 234 U- 230 Th system appears predictable, allowing disturbed samples to be identified and discarded, and allowing important constraints to be placed on the behavior of U and Th during diagenesis.

Following earlier work (7, 8), we consider $\delta^{234}U(T)$ to be the most reliable quantitative test of alteration of the coral skeleton. With only a few exceptions (5, 22), diagenesis appears to shift both $\delta^{234}U(T)$ and the ²³⁰Thage toward elevated values, and this general correlation has been well documented (3–5, 23). Gallup *et al.* (24) demonstrated that a roughly linear correlation exists between ²³⁰Thage and $\delta^{234}U(T)$ in ~200 ka Caribbean reefs. This is consistent with a diagenetic mechanism that adds both foreign ²³⁰Th and ²³⁴U continuously and linearly to the coral skeleton.

Aside from these Caribbean data, only the MIS 5.5 observations for Western Australia (7, 8) and these MIS 9 interglacial results for Henderson Island are of sufficient number

and precision to test the validity of any given model of diagenesis. A striking result is that the ²³⁸U-²³⁴U-²³⁰Th system exhibits similar

diagenetic behavior at all three reef localities. Although exceptions do occur (for example HEN 1-21, HEN 1-22, and HEN 4-12 in the



Fig. 1. Location of Henderson Island which, together with Pitcairn, Ducie, and Oeno islands, compose the Pitcairn Island Group, located near the summit of the East Pacific Rise, \sim 2100 km west of Easter Island. Henderson Island is tectonically stable, and its slow isostatic uplift [<0.1 m/ka (*18*)], in response to volcanic loading by the emplacement of Pitcairn Island at \sim 0.8 million years ago (Ma), need not be considered when resolving MIS 9 sea-level change. (Inset) Composite geological cross-section of Henderson Island [modified from (*18*)]. The oldest exposed reefs occur in the center of the island and represent a major atoll construction phase; MIS 15 corals were sampled from the interior fossil lagoon. MIS 9 fringing reefs occur at the seaward margin of the early-formed atoll.



Fig. 2. (A) δ^{234} U(7) and (C) sample elevation versus ²³⁰Th-age for "reliable" MIS 9 corals from Henderson Island. Duplicate analyses in (A) are indicated by gray ellipses. The lower precision result for HEN 2-7 is represented by a dashed ellipse. Shown also in (C) are the Devils Hole δ^{18} O Nevada temperature proxy (11), the North Atlantic Site 980 δ^{18} O sea-level record (32), and the Milankovitch solar insolation curve for July 65°N. Sea-level and 65°N July insolation curves for MIS 5 are shown in (B) for comparison.

MIS 9 Henderson Island data set), approximately the same broadly linear relationship between the ²³⁰Th-age and $\delta^{234}U(T)$ can be found in the reefs of Henderson Island (~330 ka), the Caribbean (~200 ka), and Western Australia $[\sim 125 \text{ ka}; \text{Web fig. 1} (16)]$. The three data sets appear consistent with a common alteration process independent of local climate, whether it follows the combined ²³⁰Th-²³⁴U linear uptake model proposed by (24) or a more elaborate open-system model (25, 26). Assuming continuous uptake of external ²³⁴U and ²³⁰Th, the rates must be approximately linear, and the ratio of the rates of ²³⁴U to ²³⁰Th addition approximately fixed, irrespective of location. Similar diagenetic shifts in U-Th appear to be occurring at a fine (millimeter to centimeter) scale in the Henderson Island reefs. Replicate results for separately processed pieces of samples HEN 2-7 and FH 328 show that older ²³⁰Th-ages are correlated with more elevated $\delta^{234}U(T)$. The degree of alteration of the coral skeleton is variable, but is consistent with the diagenetic

whole. Corals with the lowest $\delta^{234}U(T)$ are assumed to have undergone minimal diagenetic exchange of U and Th, providing a reliable constraint on the seawater ²³⁴U/²³⁸U during the MIS 9 interglacial. In Web fig. 1 (16), no Henderson Island initial δ^{234} U lies below the δ^{234} U(T) = 149 ± 1‰ contour for present-day seawater, excluding the few erroneous data points that do not lie on the same diagenetic trend as shown by the rest of the data. Isotopic studies of \sim 200 and \sim 125 ka corals (6, 7, 24) indicate that the marine δ^{234} U was within error of the present-day value during the previous two interglacial periods. There is some indication that the marine δ^{234} U was also near 149‰ during the 83 ka interstadial event (24). Our new Henderson Island data show that even at ~330 ka, the seawater δ^{234} U appears to have been within error of 149‰, and we conclude that the marine ²³⁴U/²³⁸U has returned to essentially the same value during each of the past four interglacial periods.

behavior exhibited by the reef system as a

Two interpretations of the reliable U-series data for the MIS 9 Henderson Island reefs are possible, representing limiting cases of a range of intermediate models. In the first case, it is assumed that all corals formed during a continuous episode of reef growth, within a single and prolonged sea-level highstand correlating with MIS 9.3. This interpretation assumes the different sample elevations [between <2 and 29 m above the present mean sea level (MSL) datum] reflect the variable water depths in which corals can grow. Today at Henderson Island, most corals live in an 18-m depth range, between 2 and 20 m below MSL (27). In this case, our ²³⁰Th-ages suggest that high interglacial sea levels persisted from at least 334 ± 4 to 306 ± 4 ka (weighted mean of two results for

HEN 2-2), and possibly later, until 293 \pm 5 ka if the less precise result for HEN 2-7 is also considered (Fig. 2A). Considering, for the moment, precise results only, the data give a minimum duration of 20 ka and a maximum duration of 36 ka for the MIS 9 sea-level high-stand, taking into account the 2σ age uncertainties. The latter interval is very long compared with the duration of the Last Interglacial (Fig. 2B), but, given the extremely old age of these samples, it is possible that even "reliable" data points have still been disturbed by minor diagenesis, shifting their ²³⁰Th-ages toward older values despite our screening efforts.

The second, and preferable, explanation assumes that all "reliable" samples are pristine and several discrete reef-building episodes occurred during multiple sea-level high-stands. Figure 2C considers an alternative sea-level curve for MIS 9, assuming all corals formed near the sea surface, at MSL. The data show several distinct oscillations in sea level, which may be correlated with the MIS 9.3 interglacial and MIS 9.1 and MIS 8.5 interstadials, respectively. Our results suggest that sea levels approached peak interglacial values near 324 ± 3 ka and high sea levels persisted for up to 8 ka. Sea levels then began to fall toward glacial values near 318 ± 3 ka (weighted mean of two results for HEN 5-6). Subsequent "interstadial" oscillations in sea level attained their maximum values near 306 \pm 4 and 293 \pm 5 ka, in-phase with Milankovitch insolation peaks at ~311 and ~ 290 ka, respectively (28). Two critical observations support this latter scenario. First, Montastrea sample HEN 4-1, dated at 334 ± 4 ka, probably correlates with the MIS 10/9 deglacial sea-level rise, while the sea surface was still significantly lower than at the interglacial maximum. As a comparison, living Montastrea corals on the Great Barrier Reef, Australia, reside only in the upper 15 m of the water column. If the same ecological conditions can be assumed for the Montastrea species at Henderson Island, then the implication is that at least a 5 m rise in sea level must have occurred between 334 and 324 ka. This oscillation in sea level would have exceeded 20 m if HEN 1-26 grew in deeper water than HEN 4-1. Similarly, Montastrea sample HEN 1-10 occurs ~28 m stratigraphically lower than the clustering of samples correlating with the MIS 9.3 interglacial. This implies a sea-level fall of at least 13 m between 318 \pm 2 and 317 \pm 5 ka. Second, independent field observations suggest that the "MIS 9.3" samples (comprising massive corals within well-lithified reef complexes) formed during a prolonged episode of high and stable sea level, whereas the younger "interstadial" samples (composed of smaller corals within reef units that drape the lower part of the MIS 9.3 complexes) formed subsequently, during one or more lower and shorter lived sea-level still-stands.

The true sea-level curve for Henderson Island probably lies somewhere between the two end-member cases we present here. However, our results cannot resolve this. Importantly, the earliest phase of MIS 9 reef growth on Henderson Island, dated at 334 \pm 4 ka, is consistent with the only other reliably dated TIMS Useries observation for reefs that formed near the MIS 9 interglacial: a coral sample recovered from a drowned carbonate platform in the Huon Gulf, Papua New Guinea, and correlated with the preceding MIS 10 sea-level low-stand, has a slightly earlier ²³⁰Th-age of 348 \pm 10 ka (29). The Henderson Island sea-level curve in Fig. 2C also shows a very good correspondence with the Devils Hole (Nevada, USA) DH-11 paleoclimate record (11, 30), which is the only other independently dated TIMS U-series record spanning the MIS 9 interglacial interval. The DH-11 record shows that air temperatures over Nevada attained their maximum values near 335 \pm 8 ka. This is coeval with the earliest recorded episode of reef growth (at 334 ± 4 ka) on Henderson Island, although the combined U-series age uncertainties preclude an exact comparison of the two records. The Devils Hole chronology implies that interglacial climates persisted for ~ 20 ka in the Nevada region during MIS 9.3. This is in good agreement with the duration that we observe from the Henderson Island coral reef results.

Our Henderson Island results are consistent with the idea that interglacial climates are forced by orbitally induced Northern Hemisphere summer solar insolation changes centered on 65°N. The earliest high sea levels within the MIS 9 interglacial, dated between 334 ± 4 and 324 ± 3 ka, are either coincident with or slightly postdate the timing of peak insolation at 333 ka (*31*).

References and Notes

- M. M. Milankovitch, Canon of Insolation and the Ice-age Problem (Königlich Serbische Akademie, Belgrade, Yugoslavia, 1941); J. Imbrie, K. P. Imbrie, Ice Ages: Solving the Mystery (Enslow, Short Hills, NJ, 1979).
- L. R. Edwards, J. H. Chen, G. J. Wasserburg, *Earth Planet. Sci. Lett.* 81, 175 (1986).
- E. Bard, B. Hamelin, R. G. Fairbanks, *Nature* 346, 456 (1990).
- J. H. Chen, H. A. Curran, B. White, G. J. Wasserburg, Geol. Soc. Am. Bull. 103, 82 (1991).
- M. Stein et al., Geochim. Cosmochim. Acta 57, 2541 (1993).
- B. J. Szabo, K. R. Ludwig, D. R. Muhs, K. R. Simmons, Science 266, 93 (1994).
- C. H. Stirling, T. M. Esat, M. T. McCulloch, K. Lambeck, Earth Planet. Sci. Lett. 135, 115 (1995).
- C. H. Stirling, T. M. Esat, K. Lambeck, M. T. McCulloch, Earth Planet. Sci. Lett. 160, 745 (1998).
- E. Bard et al., Geophys. Res. Lett. 23, 1473 (1996).
 T. M. Esat, M. T. McCulloch, J. Chappell, B. Pillans, A.
- Omura, Science **283**, 197 (1999).
- 11. I. J. Winograd et al., Science **258**, 255 (1992).
- 12. G. M. Henderson, N. C. Slowey, *Nature* **404**, 61 (2000).
- 13. D. B. Karner, R. A. Muller, Science 288, 2143 (2000).
- X. Luo, M. Rehkämper, D.-C. Lee, A. N. Halliday, Int. J. Mass Spectrom. Ion Processes 171, 105 (1997).

- C. H. Stirling, D.-C. Lee, J. N. Christensen, A. N. Halliday, *Geochim. Cosmochim. Acta* 64, 3737 (2000).
- 16. Supplementary material is available at www. sciencemag.org/cgi/content/full/291/5502/290/DC1.
- G. Paulay, Henderson Island: Biogeography and Evolution at the Edge of the Pacific Plate, E. C. Dudleys, Ed., The Unity of Evolutionary Biology, Proceedings of 4th International Congress of Systematics and Evolutionary Biology (1991), pp. 304–313.
- 18. S. G. Blake, Bio. J. Linn. Soc. 56, 43 (1995).
- 19. J. M. Pandolfi, Bio. J. Linn. Soc. 56, 63 (1995).
- 20. Following (24), MIS 9 samples with the lowest $\delta^{234}U(7)$ are considered to have undergone the least postdepositional exchange of U and Th. It follows that corals with $\delta^{234}U(7)$ values coincident with 149 \pm 1% have accurate ²³⁰Th-ages [Web fig. 1 (16)]. The $\delta^{234}U(7)$ changes by ~2.5% per 1000 years as a result of diagenesis, and a cumulative $\delta^{234}U(7)$ shift of 8% should shift the ²³⁰Th-ages beyond their ± 2 to 3-ka age uncertainties. Therefore, we reject samples with $\delta^{234}U(7)$ lying outside the range of 149 \pm 8%. Despite placing strict limits on acceptable $\delta^{234}U(7)$, it is recognized that this criterion, although essential, is not necessarily a sufficient condition to guarantee reliability. Given their relatively large age and $\delta^{234}U(7)$ uncertainties, all MIS 15 samples are considered reliable.
- 21. The remoteness of the island has reduced the input of detrital contamination, and the effect of foreign ²³⁰Th, ²³⁴U, and ²³⁸U on the ²³⁰Th-ages has been negligible. With only two exceptions (HEN 2-7 and FH 175), all samples display detrital ²³²Th concentrations within the 0.5 part per billion limit specified by modern pristine corals from oceanic islands (2, 4). Further, relatively low rainfall [~1300 to 1500 mm/ year (26)], low humidity, and relatively cool, stable subtropical air temperatures (15° to 30°C) appear to have minimized postdepositional mobilization of the U-series isotopes.
- 22. G. M. Henderson *et al.*, *Earth Planet. Sci. Lett.* **115**, 65 (1993).
- B. Hamelin et al., Earth Planet. Sci. Lett. 106, 169 (1991).
- C. D. Gallup, R. L. Edwards, R. G. Johnson, Science 263, 796 (1994).
- 25. R. Grün, F. McDermott, Quat. Sci. Rev. (Quat. Geochronol.) **13**, 121 (1994).
- G. T. Shen, R. B. Dunbar, Geochim. Cosmocim. Acta 59, 2009 (1995).
- M. Brooke, Pitcairn Island Expedition Report (Cambridge Univ. Press, Cambridge, 1992).
- 28. A. Berger, M. F. Loutre, *Quat. Sci. Rev.* **10**, 297 (1991).
- J. Galewsky, E. A. Silver, C. D. Gallup, R. L. Edwards, D. C. Potts, *Geology* 24, 819 (1996).
- 30. K. R. Ludwig et al., Science 258, 284 (1992).
- 31. Because Henderson Island is a remote outpost locality, it is possible that a small lag exists between the onset of the sea-level high-stand and the start of reef development due to coral dispersal and recolonization limitations. However, any delay should be minimized for the intense MIS 9 interglacial, and in the absence of information to the contrary, we assume that (i) the "330 ka" reefs started to colonize Henderson Island shortly (<1 ka) after sea level stabilized at the start of the interglacial period, and (ii) reef growth ceased at the termination of the interval when sea levels began to fall to glacial values. Even allowing for small shifts in the ²³⁰Th-ages due to diagenetic alteration and/or delayed reef colonization, these data still shortly postdate the insolation maximum, and will still be concordant with Northern Hemisphere Milankovitch forcing of climate.
- 32. J. F. McManus, D. W. Oppo, J. L. Cullen, *Science* **283**, 971 (2000).
- 33. We thank two anonymous reviewers for constructive comments that helped improved the manuscript and M. Johnson, C. Hall, G. Mortimer, and L. Kinsley for technical assistance. We are grateful to J. Pandolfi for providing access to samples. This research was primarily supported by the U. S. Department of Energy and the NSF and Swiss NF grants.
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Modern Human Ancestry at the Peripheries: A Test of the Replacement Theory

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The replacement theory of modern human origins stipulates that populations outside of Africa were replaced by a new African species of modern humans. Here we test the replacement theory in two peripheral areas far from Africa by examining the ancestry of early modern Australians and Central Europeans. Analysis of pairwise differences was used to determine if dual ancestry in local archaic populations and earlier modern populations from the Levant and/or Africa could be rejected. The data imply that both have a dual ancestry. The diversity of recent humans cannot result exclusively from a single Late Pleistocene dispersal.

Two conflicting evolutionary models of modern (1) human origins have emerged in the past decade (2): complete replacement, in which modern humans are a new species that replaced all archaic populations, and multiregional evolution, in which modern humans are the present manifestation of an older worldwide species with populations connected by gene flow and the exchange of ideas, resembling each other because of similar adaptations to ideas and technologies that spread across the inhabited world and because of the dispersals of successful genes promoted by selection. One place where the models have quite different predictions is at the peripheries of the human range, where the replacement theory stipulates that the ancestry of early modern populations is not among their local archaic predecessors, who often are regarded as different human species (3). Multiregional evolution, a reticulate theory, is compatible with a dual ancestry for early moderns from the peripheries. Here we examine ancestry in Australia and Central Europe, two peripheral areas with the best fossil record for the so-called transitional period, considering an early modern Australian cranium, Willandra Lakes Hominid (WLH) 50, and the two adult male crania from Mladeč, in Moravia, Czech Republic.

WLH-50 has been dated to about 15,000 to 13,000 years by gamma spectrometric Useries analysis (4) and to about double that time by electron spin resonance on bone (5). The calvarium exhibits many features that closely resemble earlier Indonesian hominids, including the Ngandong fossils of Java (6). WLH-50 is regarded as a modern human in all origins models (6, 7), whereas Ngandong fossils are often assessed as archaic humans or late surviving *Homo erectus* (8). The other possible ancestral population we tested for this male is the earlier modern human sample from Africa and the Levant of western Asia, which under the replacement theory must represent the only ancestors (Fig. 1) of the first modern humans in Australia.

In Central Europe, over 100 fragmentary specimens unequivocally associated with an early Aurignacian industry (9) were recovered from the two Mladeč Caves in Moravia, Czech Republic (10). The most complete male calvaria are from the Quarry Cave. Mladeč 5 and 6 have been likened to the temporally earlier Neandertals (11–13) [although it is recognized that they are not themselves Neandertals (10, 11)]. Neandertals, then, are the local archaic predecessors of the Mladeč folk and are potentially their ancestors. The other potential ancestors are from Qafzeh and Skhul, the earlier modern human remains in western Asia (Fig. 2), geographically and temporally the closest source of a replacing population.

The complete replacement model requires a unique relation between the early modern humans at these two peripheries and the earlier Levantines and/or Africans regarded as modern human. If evidence shows significant local ancestry for the peripheral samples, complete replacement must be wrong. To examine this issue, we tested for refutations of the hypotheses of dual ancestry (14) for WLH-50 and the Mladeč males. Obtaining a valid statistical test requires overcoming some formidable obstacles. There are only a few early modern crania complete enough to analyze, their dates are uncertain, the comparative samples are small and haphazardly preserved (15), and the traits may depend on

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