an early, massive fractionation loss of water, the residual being locked within the mantle, slowly outgassing; or a recent ($<10^9$ yr ago) catastrophic resurfacing of Venus released a large amount of water which was highly fractionated by atmospheric loss processes, resulting in a transitory, enriched D/H that is slowly returning to the steady-state value.

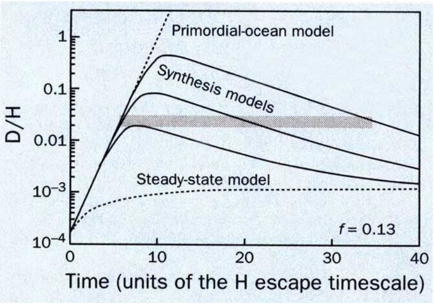
An alternative solution can be achieved from a synthesis of the primordial-ocean and steady-state D/H models. In this, it is assumed that water is in a steady state now (or in the future), but that a steady state has not always dominated. The synthesis D/H evolution model can be described by:

$$(D/H)t=(\chi Re^{-ft}+(\alpha/f)(1-e^{-ft}))/(Re^{-t}+(1-e^{-t}))$$

where $\chi$ is the initial D/H ratio, $R$ is the ratio of the initial water abundance to the eventual steady-state water abundance, and time is given in units of the hydrogen escape timescale, which is between 125 and 800 Myr (ref. 4; derivation available on request). This is a more general solution than the previous models, but reduces to the primordial-ocean model for $Re^{-t} \gg (1-e^{-t})$ and to the steady-state model for $R = 1$.

The figure shows several time evolutions for D/H, assuming that the initial and source D/H ratios are Earth-like. The simple steady-state model cannot intercept the current Venus atmosphere (represented by the bar in the figure) unless the initial and/or source D/H ratio is much larger than terrestrial, as Grinspoon noted. The primordial-ocean model does intercept the current state if the hydrogen escape timescale is near its maximum, but if it is shorter the primordial-ocean model predicts a much higher D/H ratio than is observed.

The synthesis model has characteristics of both models, showing strong early fractionation (similar to the primordial-ocean model), and then asymptotically approaching a steady-state value (as in the steady-state model). The critical transition and the maximum D/H ratio occur when the hydrogen abundance has evolved to within a factor of around 3 of the eventual steady-state abundance.



Evolution of D/H for the primordial-ocean, steady-state and synthesis models. The bar represents the possible range for current Venus atmosphere age and D/H ratio. The large uncertainty in the H escape timescale causes the large range in the age of Venus. Three curves generated by the synthesis model, with $R$ equal to 14,000 (upper curve), 2,500 (middle curve) and 360 (lower curve), are shown.

The synthesis model intercepts the current Venus state for $R$ from 360 to 14,000. For $R$ less than 360, the current D/H ratio is unreachable, given an initial D/H ratio that is Earth-like.

The model emphasizes that a minimum ratio of the initial to eventual steady-state water abundance of 360 is required to match the current D/H ratio. This implies that the initial water abundance was a minimum of 120 times the current water abundance, or the equivalent of a 1.8-m global ocean. These are conservative estimates assuming constant $f$; $f$ was probably higher in the past, allowing even higher values of $R$, perhaps as much as that for a terrestrial ocean.

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# Ice cores and mammoth extinction

SIR — The detailed records of past climate revealed by ice cores and other recent studies[1–4] have important implications for our understanding of the causes of the extinction of mammoths and other large mammal species around the Pleistocene/Holocene boundary.

The Late Pleistocene Holarctic 'mammoth fauna' consisted of a unique combination of grazing species intimately linked to a peculiar tundra–steppe environment, characterized by a dry, cold, continental climate and a complex, productive mosaic vegetation dominated by grassland. This ecosystem has no modern analogue, and many workers have suggested that its decline, and replacement by the relatively low-diversity, less productive Holocene zonation of tundra and boreal forest, led to the extinction of many megafaunal species[5,6].

It has been argued, on circumstantial evidence, that the higher biotic diversity of the Pleistocene might in some way reflect greater climatic variability than in the Holocene[5]. Recent discoveries seem to support this model. The Greenland ice cores indicate almost constant and rapid climatic fluctuations over the 100 kyr before the Holocene warming and, in strong contrast, a stable climatic signal for the Holocene itself[1]. Conceivably, the constant fluctuations of climate in the Late Pleistocene were partly responsible for maintaining a mosaic of plant communities, by a constant 'stirring', favouring a pioneering character of vegetation which supported the grazing megafauna[7]. In contrast, the unique stability of Holocene climate, indicated by the ice cores, may have contributed to the development of today's strong zonation of climax vegetation types, such as tundra and coniferous forest, unsuitable for large grazers like the woolly mammoth.

The detailed record of mammoth extinction is in general agreement with the climatic changes seen in the ice cores. Before 14 kyr (12.5 radiocarbon kyr), the woolly mammoth inhabited the whole of northern Eurasia. At around that time, in keeping with broad-scale warming and forest spread in northern Eurasia, the mammoth's range became restricted to Arctic Siberia, as if 'retreating' to the north[8]. Although the Arctic also experienced important vegetational change, mammoths could survive there for a few thousand years. Around 11.5 kyr, however, there was a second major event, evidenced by the appearance of a myriad of thaw lakes all over the unglaciated Arctic[8], marking the final demise of the tundra–steppe biome.

This event corresponds to the beginning of the period of stability documented by the curve from the GRIP ice core from Summit, Greenland, as a rise at 11.5 kyr, reaching a plateau at around 10 kyr. By 10.5 kyr (9.0 radiocarbon kyr), mammoths were extinct everywhere except the high Arctic island of Wrangel, where a dwarfed, insular population survived on relict tundra– steppe vegetation[9].

One problem of the climatic model of extinction has been to explain how woolly mammoth and other tundra–steppe mammals survived earlier interglacials, generally interpreted as climatic cycles of afforestation analogous to the Holocene. Some palaeontologists have proposed that the vegetation of the interglacials, in fact, differed from that of the Holocene. In northeast Siberia, for example, several 'forest' intervals correlated with interglacials have been recorded, but their vegetation differed from modern larch-dominated taiga. The main tree species was birch, and there was a substantial grass component, while insect faunas preserved some steppe

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species, indicating a habitat that could support grazing mammals[10].

The GRIP core seemed to corroborate a difference between Holocene climate and that of previous interglacials by showing major fluctuations within the 'last interglacial' around 120 kyr. The veracity of this part of the core has been questioned, however: the 'fluctuations' may be due to folding; moreover, they are not seen in some other ice-core and oceanic sequences[11]. On the other hand, independent lines of evidence corroborate Eemian inconstancy, including data from the crucial terrestrial realm. Data from a lake core in France[2] indicate two rapid cooling events within the last interglacial, including a period of reversion from forest to open subalpine vegetation. Analysis of detailed pollen records from Germany[3] suggests greater climatic instability in the last interglacial than in the Holocene. Finally, evidence of mid-Eemian cooling has come from studies in the Norwegian Sea and North Atlantic Ocean[4].

The spatial structure of the terrestrial interglacial environment requires further investigation, as does the mammoths' response to it, which clearly varied across their vast range. A crucial role may have been played by unglaciated Arctic regions in providing interglacial refuges for the tundra–steppe grazers. This pattern was again followed at the start of the Pleistocene/Holocene transition, which seems to have begun as a 'normal' interglacial. However, subsequent changes, culminating in the onset of stable climate documented by the ice cores, resulted in an irreversible turnover of the Pleistocene biota.

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# ESR ages for Krapina hominids

Sir — At the site of Krapina, 40 km NNW of Zagreb, more than 850 skeletal remains from several Neanderthal individuals were found, principally in layers 3 and 4 (refs 1, 2), associated with a Middle Palaeolithic industry[3]. We have obtained electron spin resonance (ESR)[4] and U-series dates on tooth enamel from the site (see table). Teeth from the 1899–1905 archaeological excavations of K. Gorjanoviĉ-Kramberger, stored at the Croatian Natural History Museum, were analysed as in ref. 4. External γ- and β-dose rates were estimated from U, Th and K analyses of blocks of weakly indurated sand preserved from the original excavation, found at the museum.

ESR AND U-SERIES DATES FOR KRAPINA

| Layer | Sample | ESR age (kyr) | | | U-series age (kyr) | | |
|---|---|---|---|---|---|---|---|
| | | Early uptake | Average | Linear uptake | Average | Enamel | Dentine |
| 9 | 91187A | 87±7 | 87±7 | 113±10 | 113±10 | | |
| 8 | 91182A | 109±9 | | 147±14 | | | |
| | 91182B | 90±8 | | 120±12 | | | |
| | 91182C | 88±7 | | 122±11 | | | |
| | 91182D | 90±6 | | 126±11 | | | |
| | 91182E | 94±6 | | 128±11 | | | |
| | 91182G | 88±8 | | 120±11 | | | |
| | 91182H | 93±9 | | 130±12 | | | |
| | 91182I | 90±10 | | 123±13 | | | |
| 7–8 | 91183A | 108±9 | 99±5 | 139±14 | 132±5 | 69.7±0.5 | 89.8±1.4 |
| | 91183B | 96±8 | | 128±12 | | | |
| | 91183C | 94±7 | | 127±12 | | | |
| | 91183D | 94±7 | | 128±12 | | | |
| | 91183E | 95±8 | | 126±12 | | | |
| | 91183F | 103±9 | | 135±13 | | | |
| | 91183G | 100±8 | | 132±13 | | | |
| | 91183H | 102±8 | | 135±13 | | | |
| | 91184 | 131±13 | | 152±17 | | | |
| 5–6 | 91186A | 126±11 | 130±3 | 178±17 | 167±10 | 131±1 | 223±4 |
| | 93042A | 132±13 | | 160±18 | | | $415^{+55}_{-38}$ |
| | 93042B | 132±14 | | 162±19 | | | |
| 1 | 91185A | 142±12 | 133±15 | 185±19 | 180±15 | | |
| | 91188A | 142±11 | | 192±18 | | | |
| | 91189A | 116±9 | | 163±16 | | | |

ESR dates are computed assuming 10±10% water in sediment. γ- And β-doses from sediment were determined from neutron activation analyses of sediment samples for U, Th and K. β-doses were corrected for attenuation. U-series ages were determined by thermal ionization mass spectrometry[5].

We used mass spectrometric U-series analysis of the enamel and dentine to evaluate U-uptake history, which affects the calculated ESR age[5]. Early uptake yields the minimum age for a given data set, while linear-uptake ages commonly agree with other age estimates. Equivalent early-uptake ages and U-series ages in teeth from layers 5–6 indicated early U-uptake, whereas early-uptake ages of teeth from layers 7–8 were larger than associated U-series dates, implying continuous U uptake. The respective linear-uptake or early-uptake ages of teeth from layers 1–8 were indistinguishable, with a mean of 130±10 kyr, showing that the entire fluviatile sequence was formed in the last interglacial (stage 5e), consistent with its faunal character.

Whereas hominids from beds 3–7 are all Neanderthals, layer 8 (also dated to 130 kyr) contained cranial elements of a 6–8-yr-old juvenile (Krapina 1). Some metric and morphological aspects group it with other juvenile Neanderthals, but its more pentagonal shape in rear view, higher frontal squama and some other characteristics approach the condition of early modern humans (N. Minugh-Purvis, unpublished thesis, Univ. Pennsylvania). A partial occipital bone from layer 8 (Krapina 11) lacks a suprainiac fossa, a characteristic of Neanderthals observed in occipitals from layers 3–4. These data suggest that the layer 8 hominids are possibly transitional to anatomically modern hominids, raising the question of when this taxon first appeared in Europe.

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### Scientific Correspondence

Scientific Correspondence is intended to provide a forum in which readers may raise points of a scientific character. Priority will be given to letters of fewer than 500 words and five references.