nature
SUPPLEMENTARY INFORMATION
https://doi.org/10.1038/s41586-018-0163-6
In the format provided by the authors and unedited.

Rapid recovery of life at ground zero of the end-Cretaceous mass extinction

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Supplementary Materials:

Helium Isotope Age Model

Age Interpretations

References (*39-41*)

Table S1-S3

Constructing the ^{3}He-based Age Model

The total extraterrestrial ^{3}He ($^3He_{ET}$) concentration in the transitional unit will be the sum of $^3He_{ET}$ delivered from space during its deposition in the Danian plus any $^3He_{ET}$ that comes from reworked Maastrichtian (or earlier) sediment.

Dropping the ET subscript for simplicity and using subscripts tot for total, D for Danian, and RM for reworked Maastrichtian:

$$^3He_{tot}={}^3He_D+{}^3He_{RM}$$

The Danian ^{3}He component is given by the extraterrestrial ^{3}He flux (f_3, taken from Mukhopadhyay et al.[39] divided by the total mass accumulation rate (α_{tot}) of the transitional unit. Here the term total is used to indicate that there are both reworked Maastrichtian and "new" Danian sediments contributing to the sediment flux:

$$^3He_D=f_3/\alpha_{tot}$$

The concentration of reworked Maastrichtian ^{3}He in the transitional unit depends on the concentration of ^{3}He in reworked Maastrichtian sediment (^3He_M) and the mass fraction of reworked Maastrichtian sediment (F_{RM}) in the transitional unit.

$$^3He_{RM}=F_M\,{}^3He_M$$

The ^{3}He concentration of Maastrichtian sediment is governed by the extraterrestrial ^{3}He flux and the Maastrichtian mass accumulation rate (α_M). Assuming that f_3 did not change between Maastrichtian and Danian (i.e., f_3 is constant), and further assuming no separation of extraterrestrial particles from bulk sediment during reworking:

$$^3He_M= f_3/\alpha_M$$

Combining these equations:

$$^3He_{tot}= f_3/\alpha_{tot} + F_M f_3/\alpha_M = f_3\ (1/\alpha_{tot} + F_M\,/\alpha_M) \qquad \text{[eq. 1]}$$

There are two obvious endmember scenarios of interest for understanding the transitional unit. The first assumes no reworking of Maastrichtian sediment carrying pre-impact extraterrestrial ^{3}He. In this scenario, F_M=0. Rearranging equation 1 to solve for mass accumulation rate yields:

$$\alpha_{tot} = f_3/{}^3He_{tot} \qquad \text{[eq. 2]}$$

In this scenario α_{tot} is a firm lower limit on the sediment mass accumulation rate.

A second endmember scenario of interest assumes that the transitional unit was deposited so quickly that syndepositional (i.e., Danian) extraterrestrial ^{3}He accumulation is negligible. In this case the first term in equation 1 is negligible. In this scenario, we can solve for a firm upper limit to the mass fraction of Maastrichtian sediment in the transitional unit.

$$F_M = \alpha_M \, {}^3He_{tot}/f_3 \qquad \text{[eq. 3]}$$

We measured 8 samples of the transitional unit for ^{3}He (Extended Data Table 1). Although there is some variability among these measurements, there is no obvious trend with depth. We therefore use the mean value of these samples in our computations:

$$^3He_{tot} = 0.005 \pm 0.002 \text{ pcc/g } (1\sigma \text{ standard deviation})$$

Estimated sediment mass accumulation rates in the Maastrichtian are poorly known, but we assume a typical value of $\alpha_M \sim 0.44$ g/cm2/kyr, recognizing this is an approximate calculation.

We assume the extraterrestrial ^{3}He flux is the same as determined by (*37*):

$$f_3 = 0.106 \text{ pcc/cm}^2\text{/kyr}$$

Using equation 3 to solve for an upper limit on the fraction of Maastrichtian sediment in the transitional unit yields the remarkably low value of $F_M = 2\%$. Even assuming an order of magnitude faster mass accumulation rate (~5 g/cm^2/kyr) still yields a value of just ~20%. Thus the ^{3}He data indicate that the transitional unit must be dominated by post-impact sediment rather than reworked material (unless extraterrestrial ^{3}He has been very effectively removed from the pre-impact sediment prior to redeposition).

Now considering the second endmember scenario, no reworked Maastrichtian sediment at all in the transitional unit, equation 2 yields a lower limit to the mean mass accumulation rate of the transitional unit of $\alpha_M = 21$ g/cm^2/kyr. Using the measured dry bulk density of the transitional unit of 2.53 g/cm^3, this corresponds to a linear sedimentation rate of ~10 cm/kyr.

Using this lower limit to the linear sedimentation rate, the 76 cm of the transitional unit must have been deposited in < 8 kyr. Note that even a tiny fraction of reworked Maastrichtian sediment would drastically reduce this value (i.e., at 2% reworked Maastrichtian sediment, the transitional unit would be inferred to have accumulated on a timescale too short for detection with the ^{3}He method, < ~ kyr).

Extended Data Table 1 also provides an age model based on this endmember scenario, with the bottom-most sample defined as t=0. In the absence of densely spaced and replicated ^{3}He data, for this calculation we use the mean extraterrestrial ^{3}He concentration of the entire 76 cm of the transitional interval, i.e., the mean sedimentation rate of 10 cm/kyr as computed above. This age model should be understood as providing an upper limit on the age at a given depth given the probability of reworked pre-impact ^{3}He in the transitional unit.

Age interpretations

This paper hinges on robust age interpretations for two key events which are clearly expressed the paleontological record: the first appearance of life in the crater in the upper part of the transitional unit and the establishment of a healthy, productive ecosystem at the base of the Danian limestone.

The most important of these two events is the establishment of a productive ecosystem in the early Danian. Fortunately, this is also the event for which we have the highest confidence age control for the establishment of a productive ecosystem in the early Danian. The lowermost sample in this limestone contains nannoplankton bloom taxa, geochemical markers for high productivity, and a multilayer benthic community that includes diverse and abundant benthic foraminifera and a diverse set of macrobenthic trace fossils. It also contains the lowest occurrence of the key planktic foraminifer *Parvularugoglobigerina eugubina*. This datum defines the base of Planktic Foraminifer Zone Pα, which occurs 30 kyr after the K-Pg boundary, according to the paleomagnetic timescale calibration of Cande and Kent[39] (see also[18,29]). An alternate calibration[40] gives an age 40 kyr after the impact. A difference of 10 kyr between these two calibrations is negligible, and does not change our key result, that the recovery of primary production in the Chicxulub Crater was significantly faster than nearby Gulf of Mexico and North Atlantic sites, which took 300 kyr or longer to achieve similar recovery[10]. A potentially greater source of error is whether or not the base of the limestone is the true base of Zone Pα or whether a condensed interval or period of non-deposition occurs between the lowest occurrence of *P. eugubina* and the top of the transitional unit. We are confident that very little time could be missing from Zone Pα for several reasons. The lowermost few samples are dominated by primitive early Danian forms, primarily *P. eugubina, P. extensa, P. alabamensis*, and *Guembelitria cretacea*[41]. Other taxa that originate in Zone Pα are either very rare or absent in this lowermost sample, including the genera *Praemurica, Eoglobigerina*, and *Chiloguembelina*. The absence of these more advanced forms suggests that this lowermost sample is early in the zone. We are therefore confident that the establishment of a productive, healthy ecosystem occurred in the Chicxulub Crater within approximately 30 kyr of the impact.

The appearance of life in the Chicxulub Crater within years of the impact is also a highly significant result. Fortunately, we have a number of ways to constrain this occurrence (Figure 3). Based on the biostratigraphy discussed above, we know that the burrows and survivor microfossil species in the upper portion of the transitional unit appeared no later than 30 kyr after the impact. The minimum amount of time, based on the physical and geochemical properties of the rock and assumptions about crater processes, is even shorter, on the order of years. To better constrain this, we utilize the abundance of ^{3}He in the transitional unit. As described above, ^{3}He provides a maximum duration of 8 kyr, assuming none of the ^{3}He is reworked. If we assume that even a small amount of ^{3}He is reworked (very likely, given the prevalence of reworked microfossils), then the transitional unit was deposited in a period of time below the resolution of the ^{3}He proxy, $< \sim 1$ kyr.

The most likely mechanism to explain such rapid deposition of fine grained material is settling from suspension from water made turbid by immediate post-impact wave energy. The lower portion of the transitional unit is interspersed with higher energy deposits which record the waning energy of tsunami, seiche and other water mass movements generated by the impact resurge, and platform margin collapses. Our interpretation of sedimentary settling from turbid water is bolstered by the homogeneous sedimentary makeup of the unit, as well as Site M0077's position on the bathymetric high of the peak ring. To further refine the amount of time represented by this unit we can apply Stokes' law (assuming a water depth of 650 m, a minimum particle size of 2 μm, and applying the density of carbonate – 2.7 g/cm^3), which indicates the smallest particles in this unit took approximately 6 years to completely settle out of suspension. This is likely over estimates the true settling time, as most of the grains are larger than 2 μm and the presence of multiple laminae in the lower portion of the unit indicate that settling wasn't the only process by which this unit was deposited. Despite these caveats, Stokes' Law provides a useful constraint on the time scales involved, and allows us to state with confidence that life first appeared in the crater within years after the impact.

Supplemental References

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