level for D_0 of 1 and 2 mm. Evidently the data show large real differences in drop size characteristics. They also suggest that use of data from a conventional (single-polarization) radar, with an assumed drop-size distribution, may lead to large errors in computation of localized volumes of high rainfall rate.

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1. Battan, L. J. *Radar Observations of the Atmosphere*, 89–93, 85, 40 (University of Chicago Press, 1973).
2. Seliga, T. A. & Bringi, V. N. *J. appl. Met.* **15,** 69–76 (1976).
3. Pruppacher, H. R. & Beard, K. V. *Q. Jl R. met. Soc.* **96,** 247–256 (1970).
4. Atlas, D. & Ulbrich, C. W. *J. Rech. Atmos.* **8,** 275–298 (1974).
5. Bringi, V. N., Cherry, S. M., Hall, M. P. M. & Seliga, T. A. *Antennas and Propagation* (IEE, Conference Publication 169, London, 1978).
6. Best, A. C. *Q. Jl R. met. Soc.* **76,** 302–311 (1950).
7. Marshall, J. S. & Palmer, W. M. K. *J. Met.* **5,** 165–166 (1948).

An extraterrestrial event at the Cretaceous–Tertiary boundary

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Closely spaced samples from an uninterrupted calcareous pelagic sequence across the Cretaceous–Tertiary boundary reveal that the extinction of planktonic Foraminifera and nannofossils was abrupt without any previous warning in the sedimentary record, and that the moment of extinction was coupled with anomalous trace element enrichments, especially of iridium and osmium. The rarity of these two elements in the crust of the Earth indicates that an extraterrestrial source, such as the impact of a large meteorite may have provided the required amounts of iridium and osmium.

THE Cretaceous–Tertiary boundary seems to be the only major boundary in the stratigraphic record which does not become diffuse when studied in detail[1,2]. On the contrary, all over the world the boundary can essentially be referred to one single bedding plane, even in the most complete marine sections (Gubbio, Italian Appennines[3]; Zumaya, Northern Spain[4,5]; El Kef, Northern Tunisia[6]; and many DSDP holes[7,8]). Planktonic Foraminifera occur abundantly in these sections and thus provide one of the best available ways of following the extinctions at the end of the Cretaceous[1]. This extinction and subsequent resurrection has been studied in detail in the unusually complete and thick calcareous pelagic section of Caravaca in South-east Spain[9]. Here, the topmost Maastrichtian and lowermost Palaeocene biozones (the *Micula prinsii* Zone, P. Nielsen, personal communication and the *'Globigerina' eugubina* Zone respectively) have been demonstrated. A 10-cm thick 'intermediate' bed also occurs between these zones characterized by a threefold increase of clay minerals and a peculiar indigenous fauna (J.S. in preparation). Information from the other sections mentioned above, although less complete, is compatible (Fig. 1). In the >100-m thick youngest Maastrichtian marls of the Caravaca section the rich, tropical association of planktonic Foraminifera and nannofossils[9,10] shows no significant changes up to the very last centimetre; here almost the entire association disappears within 0–5 mm. At a Maastrichtian sedimentation rate of 7±3 cm kyr^{-1} (Fig. 1) this implies that the extinction took place within ~200 yr (ref. 1).

The impoverished association in the subsequent 10 cm intermediate bed is dominated by benthonic Foraminifera and relicts of the Cretaceous planktonic fauna, like *Hedbergella monmouthensis* (Olsson), *Globigerinelloides aspera* (Ehrenberg), *G. messinae* (Brönnimann) and *Guembelitria cretacea* (Cushman). The amazingly sharp limits of this level are apparently preserved owing to a temporarily decreased rate of burrowing, because all other sediments in the section are strongly bioturbated.

At the top of this intermediate bed the new Tertiary planktonic fauna suddenly appears in great numbers. Accompanied by the sole survivor of the terminal Cretaceous 'holocaust', *Guembelitria cretacea*, this new fauna diversifies, and shows a rapid succession of different dominant species in the lowermost 50 cm of the Palaeocene, representing the entire '*G*'. *eugubina* Zone[1] (Fig. 1). Hereafter the facies becomes similar to that of the Upper Cretaceous, exhibiting the same, normal, slow evolutionary changes in fauna and flora.

Analyses

To obtain more information about the extinction event (to sort out some of the current extinction models[2]), trace elements have been analysed by instrumental neutron activation (NAA) on 100 bulk samples closely spaced around the boundary: 17 elements were detected throughout the section and 10 more

Table 1 Anomalous trace element enrichments in the lowermost Tertiary of the Barranco del Gredero, Caravaca, South-east Spain

	Upper Cretaceous					Intermediate bed				Lower Palaeocene				
	$\bar{X}$*		s†	$\overline{c.v.}$	n	$\bar{X}$		$\overline{c.v.}$	n	$\bar{X}$		s	$\overline{c.v.}$	n
Ir	0.13	p.p.b.	—	—	2	25.5	p.p.b.	—	2	0.34	p.p.b.	—	—	1
Os	0.08	p.p.b.	—	—	2	16.1	p.p.b.	—	2	0.41	p.p.b.	—	—	1
Ni	24.2	p.p.m.	—	—	2	1065.7	p.p.m.	4	6	40.6	p.p.m.	14	13	8
Co	9.06	p.p.m.	2.8	3.4	28	270	p.p.m.	3	4	5.59	p.p.m.	2.5	4	65
Cr	56.9	p.p.m.	20	3.3	28	499	p.p.m.	2.5	4	69.6	p.p.m.	19.3	2.8	63
As	2.07	p.p.m.	1.23	12.5	16	225.8	p.p.m.	12	4	1.66	p.p.m.	1.5	13.5	31
Sb	0.35	p.p.m.	0.09	14.5	19	7.01	p.p.m.	10	4	0.23	p.p.m.	0.08	16	24
Se	0.073	p.p.m.	—	—	2	5	p.p.m.	—	2	0.138	p.p.m.	—	—	1

* Sample mean.

† Sample standard deviation.

‡ Mean coefficient of variation of the analytical error (%).

§ Number of analyses.

Analytical error for Ir, Os, Ni and Se for high values better than 2%, for low values better than 10%.

Table 2 Correlation coefficient of 17 (trace) elements analysed at IRI, Delft

	Al	Ca	Sc	V	Cr	Mn	Fe	Co	Rb	Cs	La	Ce	Sm	Eu	Yb	Hf	Th
Ca	−0.94																
Sc	0.97	−0.95															
V	0.96	−0.94	0.96														
Cr	0.86	−0.86	0.89	0.91													
Mn	−0.61	0.54	−0.59	−0.56	−0.5												
Fe	0.96	−0.94	0.97	0.94	0.85	−0.6											
Co	0.87	−0.83	0.84	0.82	0.75	−0.66	0.81										
Rb	0.82	−0.82	0.81	0.74	0.63	−0.61	0.85	0.7									
Cs	0.72	−0.73	0.73	0.63	0.51	−0.51	0.77	0.57	0.96								
La	0.6	−0.67	0.71	0.66	0.72	−0.21	0.67	0.42	0.53	0.49							
Ce	0.82	−0.84	0.89	0.8	0.74	−0.42	0.89	0.63	0.79	0.78	0.76						
Sm	0.52	−0.57	0.61	0.56	0.53	−0.16	0.58	0.39	0.43	0.35	0.86	0.58					
Eu	0.45	−0.54	0.58	0.51	0.59	−0.11	0.54	0.33	0.4	0.47	0.75	0.73	0.46				
Yb	0.14	−0.26	0.28	0.23	0.33	−0.12	0.23	0.05	0.16	0.21	0.76	0.43	0.55	0.75			
Hf	0.88	−0.86	0.87	0.82	0.77	−0.56	0.88	0.8	0.88	0.77	0.67	0.77	0.59	0.46	0.27		
Th	0.96	−0.94	0.97	0.92	0.83	−0.6	0.98	0.81	0.9	0.83	0.69	0.89	0.59	0.56	0.27	0.92	
Insoluble residue	0.88	−0.87	0.91	0.85	0.78	−0.47	0.93	0.7	0.83	0.76	0.69	0.87	0.6	0.54	0.24	0.83	0.92

93–97 pairs in correlation.

were detected in the intermediate bed only. Furthermore, we analysed five samples for iridium, osmium, selenium and nickel by radiochemical means, encouraged by a recent report of Alvarez *et al.*[12] on anomalously high levels of iridium at the boundary in the previously mentioned Gubbio section (Fig. 2, Table 1). The γ-ray countings show that the ^{184}Os/^{190}Os isotopic ratio in sample III (Fig. 2) is indistinguishable, within experimental error (0.1%), from the isotopic ratio in common terrestrial osmium.

Just like the planktonic fauna, none of these trace elements shows any positive or negative trend or an enrichment when approaching the extinction level. Most elements correlate nicely with the insoluble residue content (Table 2) and show a similar rise in the intermediate bed (Fig. 2). In the basal few centimetres of this bed, however, immediately above the extinction level, iridium, osmium and arsenic occur in highly anomalous quantities (450, 250 and 110 times normal, respectively) and to a lesser extent Cr, Co, Ni, Se and Sb (9, 30, 44, 40 and 20 times normal, respectively). As, Co, Ni, Cr, Se and Sb may be derived from terrestrial source rocks. However, as Alvarez pointed out, it would be very difficult to accept a similar origin for iridium and osmium, as these elements are greatly depleted in the crust of the Earth, estimated at 0.05–0.1 parts per 10^9(p.p.b.)[11], in comparison with the average of the Solar System.

From these observations we find: (1) the extinction event was extremely abrupt, without previous warning signal whatsoever; and (2) the anomalously high amounts of iridium and osmium are clearly linked with the event.

Discussion

All the complete sections mentioned above contain almost exclusively Foraminifera and nannofossils, so any pronouncement on the syn- or diachronism of extinction with other groups or organisms remains somewhat speculative.

Attempts to achieve this correlation by palaeomagnetic means are widely debated[13–16], but irrefutable evidence for a diachronous extinction has never been produced[1]. Russell[2] has recently reviewed the current extinction models. He concluded

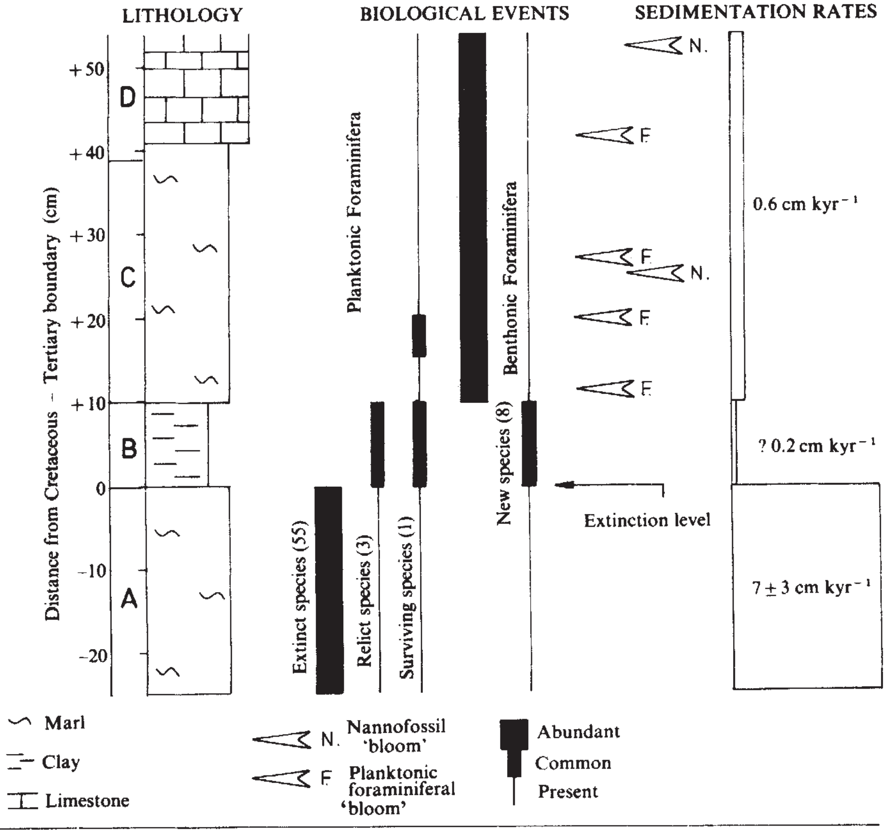

Fig. 1 The Cretaceous–Tertiary boundary interval in the Barranco del Gredero, Caravaca, South-east Spain. A, Micula prinsii Zone; B, 'intermediate' bed; C, *Globigerina eugubina* Zone; D, *Globigerina pseudobulloides* Zone.

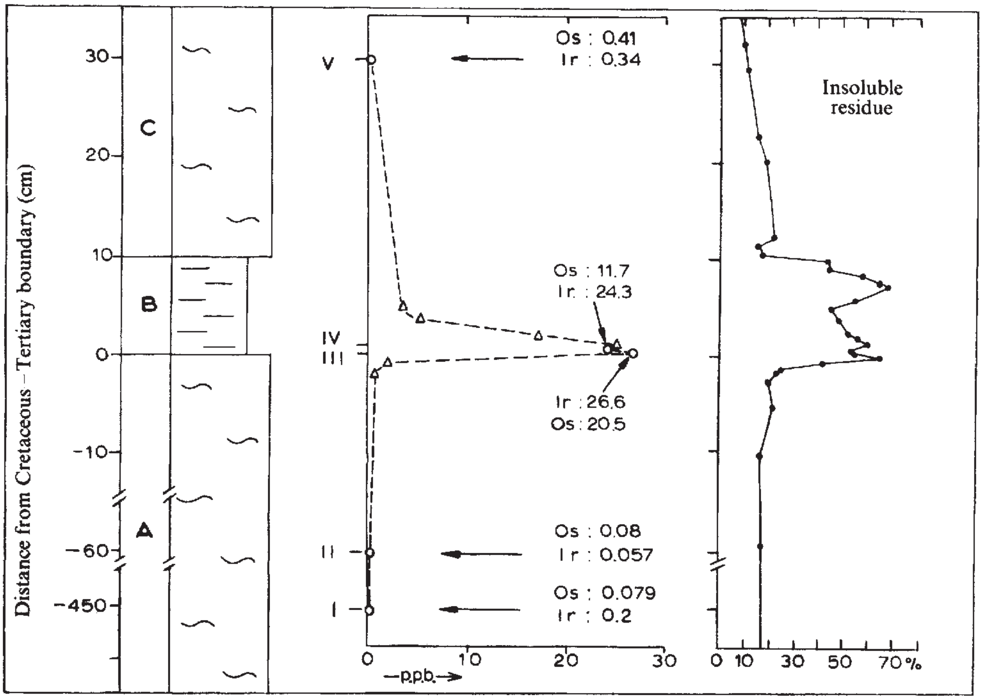

Fig. 2 Iridium, osmium and insoluble residue data from the Cretaceous–Tertiary boundary in the Barranco del Gredero. The iridium data are plotted. ○, I-V Samples analysed at the Institute for Nuclear Sciences, Gent, Belgium. Δ, Preliminary Ir analyses, communicated by W. Alvarez. A, Micula prinsii Zone; B, 'intermediate' bed; C, '*Globigerina*' *eugubina* Zone.

that none of the existing models is entirely satisfactory, but that only a very short event, which a great part of the biosphere could not tolerate, may explain the known facts. The above mentioned points support this view.

Current extinction models may be classified in two ways; the gradual versus the catastrophic or the terrestrial as opposed to the extraterrestrial models. Most terrestrial models (nutrient depletion[17], climatic deterioration[18], rise in CCD[19], CO_2–O_2 imbalance[20], secular variations[21] and increase in volcanism[22]) are essentially gradual and should leave traces in the sediment of the imminent extinctions. None has been found yet. Reports of gradual extinction[4,19] lose their credibility on more detailed inspection[1].

There remain the catastrophic models which do not have a pre-extinction signal. One such model is the recently advocated 'Arctic flushing' of cold brackish water over the ocean surface[7,23]. In this way, however, the excess of iridium and osmium cannot be explained. Extraterrestrial influences (giant solar flare[24], supernova[2,18,25] or asteroid impact[26-28]) on the other hand are geologically speaking instantaneous and in particular the latter explains the high amounts of iridium and osmium. The frequency of disastrous impacts on the Earth or the explosion of a nearby supernova have been estimated; once every 100 Myr an impact of an asteroid or comet nucleus 10–30 km in diameter[26-28] or every 70 Myr a supernova at a distance of 50 light yr occurs[2,25]. A typical iron meteorite is $\sim 2\times 10^4 - 4\times 10^5$ times, and a chondrite $\sim 6\times 10^3 - 2\times 10^4$ times, enriched in Ir and Os relative to the crust of the Earth and when such body vaporizes on impact, or is partly broken up on entry in the atmosphere, it may deliver overdoses of Ir and Os over a large area; if we assume the Caravaca values—3×10^{-8} g cm^{-2} — dispersed over the whole world and an iridium content of 5×10^{-7} g per g in a carbonaceous chondrite it may imply an impacting body of about 5 km in diameter. Geological evidence for an impact, such as a crater larger than 150 km in diameter or impact triggered sediment at the boundary have not yet been found.

The expanding shell of a supernova explosion could sweep up amounts of Ir and Os from interstellar matter.

The maximum amount that can be swept up by a supernova at 50 light yr distance is only the equivalent of the Os and Ir content of a chondrite with a diameter of 60 m. Hence it falls short by a factor of 10^6 with respect to the required amounts (E. P. J. van den Heuvel, personal communication). Also the ratio of the stable osmium isotopes ^{184}Os/^{190}Os is very similar to Solar System ratios[12]. It would be surprising if the isotopic composition in interstellar matter is within 0.1% of Solar System ratios.

Conclusions

The present evidence favours an extraterrestrial cause for the extinctions at the end of the Cretaceous. The impact of an asteroid or comet 5–15 km in diameter is the most attractive. The consequences of such an event are still poorly understood and need further investigation, as not all the facts fit this model easily.

A crucial point in the model is the near synchronous extinction of all organisms that did not cross the Cretaceous–Tertiary boundary, and the independence of the event from the known normal environmental processes going on in the latest Cretaceous.

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1. Smit, J. *Proc. Cret. Tert. Bound. Events Symp.* **II,** 156–163 (1979).
2. Russell, D. A. *A. Rev. Earth planet. Sci.* **7,** 163–182 (1979).
3. Alvarez, W. *et al. Bull. geol. Soc. Am.* **88,** 367–389 (1977).
4. Herm, D. *Z. Deut. Geol. Ges.* **115,** 277–348 (1963).
5. Percival, S. F. & Fisher, A. G. *Evolut. Theory* **2,** 1–35 (1977).
6. Donze, P. *Proc. Cret. Tert. Bound. Events Symp.* **II,** 237 (1979).
7. Thierstein, H. & Berger, W. H. *Nature* **276,** 461–466 (1978).
8. Boersma, A., Shackleton, N., Hall, M. & Given, Q. *Init. Rep. DSDP* Leg **42,** 695–717 (1978).
9. Smit, J. *Proc. Kon. Ned. Akad. Wet.* **80,** 280–301 (1977).
10. Romein, A. J. T. *Proc. Kon. Ned. Akad. Wet.* **80,** 256–279 (1977).
11. Crockett, J. H. & Kuo, H. Y. *Geochim. cosmochim. Acta* **43,** 831–842 (1979).
12. Alvarez, W. *et al. Proc. Cret. Tert. Bound. Events Symp.* **II,** 69 (1979).
13. Butler, R. F. *et al. Nature* **267,** 318–323 (1977).
14. Lerbeckmo, J. F. *et al. Nature* **279,** 26–30 (1979).
15. Alvarez, W. & Vann, D. W. *Geology* **7,** 66–67 (1979).
16. Lucas, S. G. & Rigby, J. K. *Geology* **7,** 323–326 (1979).
17. Tappan, H. *Paleogeogr. Paleoclimat. Paleoecol.* **4,** 187–200 (1968).
18. Newell N. D. *Science* **149,** 922–924 (1965).
19. Worsley, T. R. *SEPM spec. Publ.* **20,** 94–125 (1974).
20. McLean, D. M. *Science* **201,** 401–406 (1978).
21. Fisher, A. G. & Arthur, M. A. *SEPM Spec. Publ.* **25,** 19–50 (1977).
22. Vogt, P. R. *Nature* **240,** 338–342 (1972).
23. Gartner, S. & Keany, J. *Geology* **6,** 708–712 (1978).
24. Roy, J. R. *Syllogeus* **12,** 89–110 (1977).
25. Tucker, W. H. *Syllogeus* **12,** 111–124 (1977).
26. Kerr, R. A. *Science* **206,** 803–804 (1979).
27. Napier, W. M. & Clube, S. V. M. *Nature* **282,** 455–459 (1979).
28. Dachille, F. *Earth planet. Sci. Lett.* **46,** 44–52 (1977).