Fungal Proliferation at the Cretaceous-Tertiary Boundary

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The evolution of life on Earth has been interrupted by several mass extinction events. The Cretaceous-Tertiary (K-T) extinction [65 million years ago (Ma)] is associated with the impact of a large bolide (*1*). On the basis of extensive data (*2*–*4*), the K-T boundary is characterized by a palynological extinction horizon coincident with a geochemical marker bed commonly succeeded by a bed rich in fern spores (*2*–*5*).

We have found that a fungal spike occurs between the diverse Late Cretaceous palynoflora and the low-diversity fern-dominated early Paleocene assemblages in a New Zealand section. The fungal layer is coincident with the Ir anomaly marking the extinction event.

The studied K-T boundary occurs within a 10-cm-thick coal seam bounded by mudstones of the nonmarine Rewanui Coal Measures Member (upper Paparoa Coal Measures) at Moody Creek Mine, Greymouth Coalfield, New Zealand (171°16′40″E, 42°23′18″S). We identified palynomorph assemblages from consecutive 3- to 5-mm laminae through 20-cm coal and mudstone succession. One half of each sample was analyzed for elemental abundance (*6*) (table S1).

The basal 8 cm of coal hosts Late Cretaceous spore-pollen assemblages incorporating around 80 conifer, fern, and flowering plant taxa typical of complex temperate forest communities (*5*). The succeeding ~4-mm layer (Fig. 1) yielded only fungal spores and fragments of nonseptate hyphae belonging to previously undescribed species of fungi (*7*) (Fig. 1A). Overlying laminae contain low-diversity, fern-dominated assemblages. No significant macroscopic changes or clastic partings occur within the coal to suggest a change in sedimentation rate or depositional setting across the K-T boundary.

Analysis of a nearby section revealed an identical pattern of floristic turnover, indicating that the fungi-rich interval characterizes a distinct layer in the coal. The fungal acme is coincident with extinction of several miospore index taxa and an iridium abundance of ~4 parts per billion (ppb) (Fig. 1B; table S1).

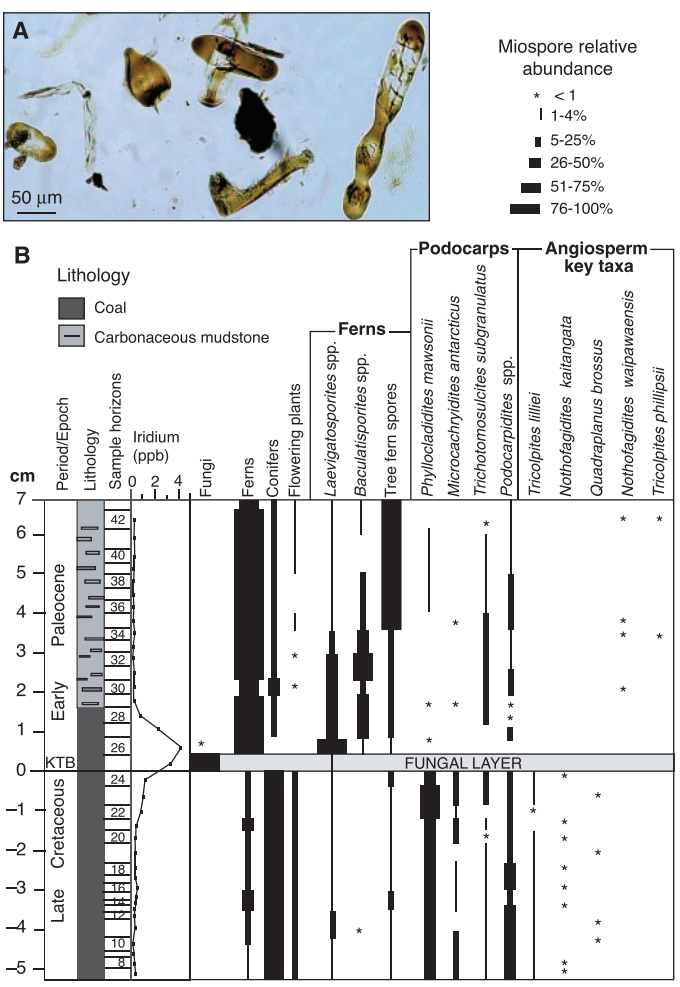

Fig. 1. (**A**) Fungal spores, *Monoporisporites* spp., aff. *Pluricellaesporites* spp. and hyphae from the "fungal spike" layer at Moody Creek Mine. (**B**) Changes in Ir concentration and relative abundance of pollen and spores across the K-T boundary at Moody Creek Mine.

This fungi-rich interval implies wholesale dieback of photosynthetic vegetation at the K-T boundary in this region. The fungal peak is interpreted to represent a dramatic increase in the available substrates for saprophytic organisms (which are not dependent on photosynthesis) provided by global forest dieback after the Chixculub impact (*5*). Post-impact conditions of high humidity and reduced solar insolation due to increased atmospheric sulfur aerosols and dust (*8*) would have favored saprophyte activity, but this interval would have been short-lived because of rapid atmospheric settling.

Fungal dominance would have lasted a few years at most, because the recovery of ferns initiates within the maximum iridium anomaly layer (Fig. 1B). This suggests rapid reestablishment of pteridophyte communities following the impact event.

A global fungal or algal (*Reduviasporonites*) spike followed by a pteridophyte-gymnosperm recovery has also been reported from the Permian-Triassic (P-Tr) boundary (*9*). The K-T and P-Tr vegetation recoveries represent similar responses to terrestrial ecosystem destabilization and collapse, although the P-Tr biodiversity crisis was more prolonged (*9*).

References and Notes

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Supporting Online Material

www.sciencemag.org/cgi/content/full/303/5663/1489/DC1
Materials and Methods
Table S1

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SUPPORTING ONLINE MATERIAL

Manuscript # 1093807

Fungal Proliferation in the Cretaceous-Tertiary Disaster Zone

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Material and Methods

Palynology

Standard palynological processing methods were employed. Slide sets were made up from material derived from two sections at Moody Creek Mine. Fig. 1 is based on a set prepared by senior author and analysed at Lund University. Material from a split of the same samples was sent for geochemical analyses. Another set was processed by Roger Tremain at Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand (IGNS). The slides were examined under transmitted light microscopy: 200-300 specimens of pollen and spores were counted from each sample, and all slides then examined for rare taxa. Slides and macerated residues of the samples are deposited at GeoBiosphere Science Centre, Lund University, Sweden and at IGNS.

Geochemical analysis

Iridium and other elemental measurements used neutron activation analysis. Samples were irradiated at the University of Missouri-Columbia Research Reactor and subsequently measured at the Lawrence Berkeley National Laboratory by Frank Asaro with the Luis W. Alvarez Iridium Coincidence Spectrometer. Iridium above the anticipated terrestrial background levels was detected in several Moody Creek Mine samples, with best precision (one sigma) of 0.006 ppb. The Ir peak (4.1 ppb) found in this high-precision analysis was much lower than the previously reported[4] peak value (70.2 ppb) obtained from a more coarsely-sampled section some metres distant, analyzed at a different laboratory.

Element abundances in Moody Creek Mine samples

Elements measured and abundance units				Ir (ppt)		Ta (ppm)		Co (ppm)		Fe (%)		Sc (ppm)		Sb (ppm)		Cs (ppm)		Hf (ppm)		Th (ppm)		Cr (ppm)		Ni (ppm)		Ce (ppm)		Tb (ppm)	
Radioactive isotopes measured				192 Ir		182Ta		60Co		59Fe		46Sc		124Sb		134Cs		181Hf		233Pa		51Cr		58Co		141Ce		160Tb	
Gamma-ray energies (keV)				316 keV-468 keV		68 keV		1332 keV		1099 keV		889 keV		1691 keV		796 keV		482 keV		312 keV		320 keV		811 keV		145 keV		879 keV	
	mm below (-) / above KTB	Sample #	Weight (mg)	Minutes																									
	107-111.5	51	59.48	1416	143	+/- 13	1.229		17.84		2.247		21,12		0.845	+/- 0.022	29.77		3.92		22.5		101.7		48.6	+/- 3.9	114.7	1.083		
	102-106.5	50	76.81	831	138	+/- 17	1.215		17.89		2.328		20.92		0.669	+/- 0.027	27.85		3.59		21.2		97.1		42	+/- 5	105.8	1.005		
	97-101.5	49	43.93	1332	134	+/- 12	1.250		14.57		2.480		21.59		0.778	+/- 0.020	30.54		3.55		22.0		100.6		41.1	+/- 3.0	108.8	0.983		
	92-96.5	48	43.80	1017	280	+/- 19	1.323		41.4		2.297		20.19		1.054	+/- 0.025	36.21		3,73		25,1		116.2		64.0	+/- 3.3	106.6	0.881		
	87-91.5	47	48.48	1209	119	+/- 13	1.233		11.86		2.524		21.67		0.797	+/- 0.021	33.01		3.50		22.3		101.8		40.9	+/- 3.5	110.4	0.992		
	82-86.5	46	47.28	1766	169	+/- 12	1.242		17.37		2.606		22.34		0.865	+/- 0.018	37.10		3.51		21.6		105.6		46.3	+/- 3.2	110.9	0.984		
	77-81.5	45	43.18	1638	165	+/- 12	1.227		18.47		2.548		21.19		0.919	+/- 0.019	36.16		3,75		20,6		103.6		45.6	+/- 3.0	105.6	0.958		
	72-76.5	44	45.60	1899	224	+/- 12	1.239		18.63		2.235		19.48		1.084	+/- 0.017	32.38		3.65		21.1		102.8		47.6	+/- 2.8	98.5	0.885		
	66.5-71.5	43	46.18	1389	143	+/- 12	1.137		25.29		2.294		19.37		0.803	+/- 0.019	26.56		3,78		21,9		97.7		50.4	+/- 3.1	100.5	0.947		
	62-66	42	46.76	1332	315	+/- 16	1.484		17.10		1.981		17.11		1.009	+/- 0.018	26.92		4.25		27.9		127.5		50.1	+/- 2.9	105.1	0.824		
	57.5-61.5	41	45.70	1530	331	+/- 15	1.431		12.78		1.863		16.52		0.920	+/- 0.016	22.21		4,48		24,2		107.6		43.2	+/- 2.7	98.9	0.749		
	53-57	40	46.89	1488	140	+/- 10	1.109		7.80		2.247		14.94		0.309	+/- 0.014	14.56		5.25		13.9		68.4		25.7	+/- 2.7	84.8	1.154		
	50.5-52.5	39	44.34	1443	142	+/- 11	1.166		8.34		2.237		16.99		0.472	+/- 0.016	19.02		5.51		17.2		85.8		28.6	+/- 2.8	100.4	0.793		
	47-50	38	45.61	330	139	+/- 21	1.143		8.16		2.340		17.70		0.483	+/- 0.032	19.63		5,54		17,4		87.4		28.2	+/- 3.1	105.3	0.809		
	43.5-46.5	37	49.03	1113	185	+/- 13	1.061		7.66		2.432		17.10		0.510	+/- 0.017	17.63		4.94		15.9		132.6		57.1	+/- 2.6	92.9	0.742		
	40-43	36	51.01	1056	133	+/- 11	1.028		7.20		2.356		15.35		0.404	+/- 0.016	14.82		5.13		13.3		71.5		25.4	+/- 2.6	77.9	0.883		
	36.5-39.5	35	48.24	900	187	+/- 14	1.134		7.04		2.244		15.60		0.411	+/- 0.018	15.33		5.26		13.7		74.0		25.3	+/- 2.7	84.3	1.063		
	34-36	34	45.33	1974	171	+/- 9	1.101		6.92		2.342		15.32		0.353	+/- 0.012	14.47		5,65		12,7		69.8		21.4	+/- 2.5	77.0	1.158		
	30.5-33.5	33	43.25	1095	111	+/- 11	1.033		6.57		2.361		14.98		0.298	+/- 0.016	12.64		5.28		11.5		63.1		20.5	+/- 2.9	67.2	1.505		
	27-30	32	39.71	1416	109	+/- 11	1.077		6.92		2.471		15.50		0.287	+/- 0.016	13.11		5.16		12.6		63.4		24.4	+/- 3.6	72.6	1.640		
	23.5-26.5	31	30.25	216	108	+/- 25	1.128		7.44		2.436		15.24		0.313	+/- 0.040	14.14		5.12		12.6		67.6		25.5	+/- 3.5	74.2	1.311		
	20-23	30	20.97	1863	259	+/- 14	1.251		9.84		1.984		16.37		0.658	+/- 0.018	19.57		5,45		18,3		90.8		33.5	+/- 2.2	101.7	0.760		
	16.5-19.5	29	14.43	1173	192	+/- 18	1.058		8.76		2.094		15.21		0.471	+/- 0.024	17.25		4.71		14.0		73.8		30.2	+/- 2.6	80.3	1.090		
	12-16	28	20.10	117	971	+/- 102	0.924		23.10		0.994		13.01		0.80	+/- 0.07	31.77		1.97	+/- 0.03	21.0		108.2		55	+/- 5	136.4	0.898		
	7-12	27	52.60	12	2116	+/- 329	0.719		26.42		0.319	+/- 0.004	9.60		0.80	+/- 0.13	17.03		1.59	+/- 0.05	27.53		106.5		27	+/- 9	99.5	0.61	+/- 0.04	
	4.5- 8.5	26	49.35	1227	4136	+/- 69	1.245		15.87		0.0931		9.68		0.788	+/- 0.020	4.30		6.03		16.79		85.3		37.3	+/- 2.9	87.4	0.922		
KTB	0-4	25	51.42	12	3184	+/- 452	0.771	+/- 0.018	18.34		0.116	+/- 0.008	15.94		0.75	+/- 0.17	7.82	+/ 0.11	4.57	+/- 0.08	12.36		64.9		23	+/- 14	92.5	1.47	+/- 0.06	
	- 1 to -4	24	51.59	24	1365	+/- 185	0.359	+/- 0.008	22.94		0.0504	+/- 0.0028	12.54		2.61	+/- 0.12	3.28	+/ 0.05	1.395	+/- 0.039	4.82		51.1		61	+/- 6	36.31	0.507	+/- 0.031	
	-4.5 to -8.5	23	51.74	21	1060	+/- 174	0.303	+/- 0.009	31.65		0.0573	+/- 0.0027	12.93		2.34	+/- 0.12	4.70	+/ 0.06	1.33	+/- 0.04	5.11		46.5		73	+/- 7	46.3	0.549	+/- 0.035	
	-9.5 to -12	22	50.99	285	1039	+/- 58	0.1740		31.92		0.051	+/- 0.007	12.14		2.02	+/- 0.06	4.32		1.023	+/- 0.021	4.31		34.6		66.5	+/- 3.3	32.02	0.465	+/- 0.014	
	-12 to -15	21	50.67	24	547	+/- 143/117	0.176	+/- 0.008	27.92		0.0598	+/- 0.0021	11.78		2.36	+/- 0.11	5.19	+/ 0.06	1.171	+/- 0.036	3.84		33.9		64	+/- 6	26.36	0.411	+/- 0.029	
	-15 to -18.4	20	42.25	51	376	+/- 74	0.164	+/- 0.006	26.06		0.0633	+/- 0.0023	11.28		2.49	+/- 0.09	9.16		1.051	+/- 0.029	3.65		27.4		64	+/- 5	36.37	0.655	+/- 0.025	
	-18.4 to -23.5	19	49.65	24	477	+/- 134/108	0.199	+/- 0.008	32.14		0.3853		10.60		2.00	+/- 0.11	11.51		0.922	+/- 0.037	3.68		25.2		77	+/- 7	38.05	0.498	+/- 0.031	
	-23.5 to -26.5	18	49.57	66	266	+/- 58	0.282		30.63		0.1398	+/- 0.0015	11.92		1.58	+/- 0.08	20.27		1.391	+/- 0.027	5.03		30.7		65	+/- 5	63.2	0.840	+/- 0.025	
	-26.5 to -28.5	17	49.44	846	292	+/- 22	0.301		29.11		0.1927		11.81		1.43	+/- 0.04	21.49		1.602	+/- 0.018	5.19		30.2	+/- 1.4	75	+/- 5	70.3	0.858	+/- 0.018	
	-28.5 to -30.5	16	50.14	102	347	+/- 51	0.366		29.02		0.2051		12.20		1.46	+/- 0.07	23.54		1.543	+/- 0.023	5.68		34.7		67	+/- 5	79.7	0.905	+/- 0.026	
	-30.5 to -32.5	15	51.63	921	279	+/- 21	0.392		31.23		0.2415		12.61		1.31	+/- 0.05	26.32	+/ 0.45	1.741	+/- 0.019	6.11		35.8	+/- 1.0	78	+/- 6	89.6	0.971	+/- 0.023	
	-32.5 to -34	14	52.39	72	270	+/- 54	0.398		21.61		0.2252		11.68		1.60	+/- 0.08	25.09		1.643	+/- 0.026	5.63		35.8		71	+/- 5	83.4	0.920	+/- 0.029	
	-34 to -35.5	13	50.18	1131	260	+/- 19	0.451		24.12		0.3034		13.31		1.43	+/- 0.05	34.08	+/ 0.45	2.109		7.13		39.6	+/- 1.1	78	+/- 7	114.0	1.296	+/- 0.027	
	-35.5 to -37.5	12	51.09	63	381	+/- 68	0.445		24.59		0.2645		12.92		1.38	+/- 0.08	28.42		1.835	+/- 0.029	6.68		41.2		81	+/- 5	84.1	0.859	+/- 0.028	
	-37.5 to -40.5	11	50.90	1305	275	+/- 16	0.387		19.29		0.1942		10.62		3.13	+/- 0.08	16.14		1.380		5.00		35.7	+/- 0.8	88.1	+/- 3.2	45.2	0.447	+/- 0.011	
	-40.5 to -44	10	50.23	60	312	+/- 64	0.529		19.35		0.2908		12.56		2.53	+/- 0.10	36.49		2.115	+/- 0.030	6.99		47.2		80	+/- 5	73.5	0.736	+/- 0.025	
	-44 to -47	9	51.08	983	211	+/- 19	0.587		16.04		0.401		13.90		1.96	+/- 0.05	37.6	+/ 0.5	2.538		8.26		49.0	+/- 1.4	67	+/- 6	101.3	1.037		
	-47 to -50	8	50.44	939	211	+/- 19	0.708		16.72		0.506		15.52		1.49	+/- 0.05	43.7		3.330		9.96		55.8		69	+/- 9	123.3	1.210		
	-50.5 to -54	7	49.91	954	178	+/- 17	0.754		15.17		0.449		13.33		1.76	+/- 0.05	32.8		3.075		9.64		57.9		72	+/- 6	89.2	0.882		
	-54 to -59	6	50.06	1416	138	+/- 13	0.978		17.21		0.684		14.22		1.196	+/- 0.035	36.70		3.977		13.20		74.3		66	+/- 6	98.1	0.945		
	-59 to -64	5	50.54	1296	122	+/- 13	1.145		13.59		0.914		14.37		1.157	+/- 0.035	31.18		4.37		14.39		78.6		58	+/- 7	104.8	1.014		
	-64 to -67	4	50.95	2970	87	+/- 8	1.138		10.65		1.317		15.62		1.015	+/- 0.029	28.31		5.15		15.39		80.4		47	+/- 7	111.0	1.082		
	-67 to -70.5	3	49,35	4713	66	+/- 6	1.121		10.09		1.574		16.14		0.866	+/- 0.027	26.68		5.12		14.94		77.1		44	+/- 9	115.1	1.089		
	-70.5 to - 74.5	2	50.80	1191	70	+/- 11	1.191		10.33		1.601		15.08		0.987	+/- 0.034	23.43		4.69		14.30		79.2		45	+/- 6	97.1	0.952	+/- 0.020	
	-80.5 to -74.5	1	52,11	4008	51	+/- 6	1.106		9.44		1.952		15.87		0.769	+/- 0.026	22.28		4.92		14.30		78.3		42	+/- 7	99.1	0.975	+/- 0.021	
Estimate of precision[c]					As given in Table		2%		1%[a]		1%		1%		As given in Table		1%		1%		2%		2%		As given in Table		2%		2%	
Estimate of error in standard					2%		2.8%		1.1%		3%		6%		?[b]		6.6 %		7.1%		2.8%		3.9%		2.5%		4.9%[d]		-3%	

a Because the samples have been ground with an agate mortar and pestle, the Co error may be higher due to the grinding procedure.

b The accuracy determined about 34 years ago was 2.9%. A recent comparison with 3 NIST standards indicates the abundances are high by 12.3 +/- 2.4%.

c The precision, which is usually taken here as the one sigma value in Gaussian statistics, is the greater of the indicated value in this row or the value in the Table.
When the total coincidence counts for Ir, however, were less than 31, Poisson statistics were used and these gave the indicated asymmetric errors for the same probabilities as the Gaussian one sigma value.

d Fission corrections were not made for the Moody Creek Mine Ce abundances, and the resulting uncertainty is not included in the estimate of the accuracy although it is usually smaller.

Table S1. Element abundances in the investigated samples from Moody Creek Mine, New Zealand. Red line indicating palynological Cretaceous-Tertiary boundary. The iridium and other elemental abundance measurements were made at the Lawrence Berkeley National Laboratory by instrumental neutron activation analysis by Dr. Frank Asaro with the Luis W. Alvarez Iridium Coincidence Spectrometer.