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Supporting Online Material for

Limits for Combustion in Low O_2 Redefine Paleoatmospheric Predictions for the Mesozoic

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Supporting Online Material

Materials and Methods

All combustion experiments were undertaken in a new state-of-the-art facility (UCD Péac) that comprises a suite of six CONVIRON BDW40 walk-in plant growth rooms with full monitoring and control of climatic and atmospheric conditions. Each chamber which measures 3.7m^2 in area and 2.4m in height can concurrently control atmospheric CO_2 (380 to 2000 ppmV), O_2 (9 to 21%) and SO_2 (200 to 2000 ppbV) to within 10ppmV, 0.1% and 100 ppb respectively of set point. Chamber temperature (-5 to 40^{o}C), relative humidity (35 to 90%), light intensity (300 to 1100μmol) and photoperiod are also all tightly controlled to set point conditions. An onsite nitrogen generation plant, producing 99% pure N_2 was used to drive down the concentration of O_2 within the six growth rooms. A PP systems O_2 sensor (OP-1 O_2 probe) was used to monitor chamber O_2 which was in turn controlled by a CONVIRON controller via a solenoid system. CO_2 was supplied via direct gas injection. This system allows for a particularly fine control of the atmospheric composition within the chambers, which has not previously been achievable for combustion experiments. Oxygen level was also monitored using a hand held O_2 monitor (Honeywell, Neotronics Impulse XP personal gas detector) to confirm that the level of O_2 remained at set point during experimental burns. Due to the low oxygen environment, the nitrogen plant was modified to also provide a source of medical grade breathing air. Additional piping was added to the growth rooms to deliver breathing air to the occupants via breathing apparatus (hood).

Experimental burns were performed at 20^{o}C at O_2 concentrations between 9 and 21% (increasing at 1% increments) at ambient CO_2 (380ppm), high CO_2 (2000ppm) and all at low relative humidity (29% +/-4%). The ultimate aim of the burns was to test the combustibility of plant material (wood and moss). Raw untreated Ocote Pine [*Pinus caribaea* Morelet var. *Hondurensis (Seneclauze)* W.H. Barret and Golfari] wood sticks were selected which is cultivated in the highlands of Guatemala and Mexico and contains around 80% resin. This was chosen as it is easy to burn (more so than pine needles for example); it ignites and burns readily in ambient conditions and can be ignited whilst wet, and therefore should represent the lowest limit at which the most combustible forest material can be ignited. The originally (as purchased) 15cm by 2cm by 2cm pieces of wood were cut down to approx 5cm by 3mm by 3mm pieces for the burns to further aid ignition. Dried moss was used to assess ground fire type material combustion. A range of other materials were also used to test combustion in low O_2 conditions and their behaviour monitored. Combustion in different atmospheric oxygen concentrations was measured as either 1) production and duration of flaming and smouldering of matches, paper, candles and *Pinus caribaea* wood sticks (where matches were used to ignite the materials) or 2) temperature change (positive deviation from the temperature of the heat source hot plate) captured using continuous thermal imaging (using FLIR systems S series ThermaCam) of sphagnum moss burns using a hot plate to ignite the moss set at ~450^{o}C. Ignition of the materials under each atmospheric setting were repeated 15 times as combustion trials in ambient O_2 found 15 to be the minimum number of replicates needed to produce a statistically stable running average.

Limited Fire Data Between 250-238ma and 236-22ma is a Preservational Artefact

We attribute the limited occurrence of proxy wildfire data between 250-238Ma and 236-222Ma (Fig. 2) to a lack of suitable strata in which fire evidence is likely to be preserved. The Paleobiology Database (http://paleodb.org/) was queried for the number of terrestrial stratigraphic units for each geological age of the Mesozoic on the 26/02/2008, to provide a baseline of the abundance of suitable sections, available worldwide, that have the potential of preserving non re-worked wildfire remains. These data were plotted against the "abundance" of fires for each age unit of the Mesozoic (SOM Fig. 1A) and revealed a significant correlation between the amounts of available stratigraphic sections present on Earth with the occurrence of fires preserved throughout the Mesozoic (chi squared *p (same)* value of 0.007177).

Smith and McGowan (*1*) have shown that outcrop area is a better indicator of rock abundance than the number of stratigraphic units. In order to get a broad estimate of the potential terrestrial rock outcrop area for the Mesozoic and its affect on the fire occurrence record, the "abundance" of fires throughout the Mesozoic was plotted against the sea level curve of Haq *et al.,* (*2*)(SOM Fig. 1B). High sea level correlates with periods where there are less recorded fires (as expected). The apparent occurrence of wildfires in the fossil record is clearly controlled by the availability of suitable rock sections for study. Based on this detailed analysis of rock abundance and the availability of suitable strata (SOM Fig. 1A, B) to preserve charcoal we argue that this wildfire gap more likely represents a taphonomic (preservational) artefact than an indication of low O_2 levels during these intervals. We acknowledge however, that the detection of sub-stage level low-O_2 events are beyond the detection of the current proxy wildfire data set.

References

1. A.B. Smith, A.J. McGowan, *Palaeontology*, 50, 765 (2007).

2. B.U. Haq, J. Hardenbol, P.R. Vail. In Sea Level Changes – An intergrated Approach eds. C.K. Wilgus, B.S. Hastings, C.A. Ross, H. Posamentier, J. Van Wagoner and C.G.S.C. Kendall: *SEPM Spec. Publ.,* 42, 71-108 (1988).

Figure Captions for Supporting Online Material

Fig. 1. Rock abundance and occurrence of paleowildfire indicators. (A) Number of terrestrial stratigraphic units for each geological age, occurring worldwide (data from Paleobiology database as correct on 26/02/2008), versus occurrence of paleowildfire indicators (data from Table. 1). (B) Sea level curve after Haq *et al.,* (*2*) compared to occurrence of paleowildfire indicators (data from Table. 1).

Table 1. Nature of paleowildfire evidence and source references used to construct the Mesozoic record of paleowildfires.

SOM Table 1

Reference	Age		Location	Evidence	Description/Comments
Allen, 1998. Proc. Geol. Assoc. 109 p. 109	Early Cretaceous Purbeck-Wealden	Berriasian-Barremian - ? earliest Aptian 140-130ma	Purbeck S. England	Charcoal	Occurrence of fires well documented
Alvin et al., 1981. Palaeontology, 24 p. 759	Wealden	Barremian	Isle of Wight	Charcoal	Charcoalifed wood of several conifers including Pseudopfrenolopsis
Alvin, 1974. Palaeontology, 17 p. 587	Early Cretaceous Purbeck-Wealden	Hauterivian-Barremian (127ma)	Isle of Wight	Charcoal	Abundant charred ferns (Weichselia) occuring in gutter casts in siltstone layers. Concluded that this fern dominated community was vulnerable to the spread of fire
Belcher et al., 2003. Geology, 31 p. 1061; Belcher et al., 2005. J. Geol. Soc. Lond. 162 p. 591	Late Cretaceous	Maastrichtian (latest Cretaceous)	New Mexico	Charcoal and Polycyclic Aromatic Hydrocarbons (PAHs)	Charcoal and polycyclic aromatic hydrocarbons (PAHs) found in abundance in latest Cretaceous sediments between 15cm and 0cm prior to the K-P event
Belcher et al., 2003. Geology, 31 p. 1061; Belcher et al., 2005. J. Geol. Soc. Lond. 162 p. 591	Late Cretaceous	Maastrichtian (latest Cretaceous)	Colorado	Charcoal and PAHs	Charcoal and PAHs found in abundance in latest Cretaceous sediments between 15cm and 0cm prior to the K-P event
Belcher et al., 2003. Geology, 31 p. 1061; Belcher et al., 2005. J. Geol. Soc. Lond. 162 p. 591	Late Cretaceous	Maastrichtian (latest Cretaceous)	Montana	Charcoal and PAHs	Charcoal and PAHs found in abundance in latest Cretaceous sediments between 15cm and 0cm prior to the K-P event
Belcher et al., 2003. Geology, 31 p. 1061; Belcher et al., 2005. J. Geol. Soc. Lond. 162 p. 591	Late Cretaceous	Maastrichtian (latest Cretaceous)	North Dakota	Charcoal and PAHs	Charcoal and PAHs found in abundance in latest Cretaceous sediments between 15cm and 0cm prior to the K-P event

Belcher et al., 2003. Geology, 31 p. 1061; Belcher et al., 2005. J. Geol. Soc. Lond. 162 p. 591	Late Cretaceous	Maastrichtian (latest Cretaceous)	Wyoming	Charcoal and PAHs	Charcoal and PAHs found in abundance in latest Cretaceous sediments between 15cm and 0cm prior to the K-P event
Belcher et al., 2003. Geology, 31 p. 1061; Belcher et al., 2005. J. Geol. Soc. Lond. 162 p. 591	Late Cretaceous	Maastrichtian (latest Cretaceous)	Saskatchewan	Charcoal and PAHs	Charcoal and PAHs found in abundance in latest Cretaceous sediments between 15cm and 0cm prior to the K-P event
Bojesen-Koefoed et al., 1997. Int. J. Coal Geol. 34 p. 345	Late Jurassic	Lower-Middle Oxfordian	N.E. Greenland	Mudstone containing between 30-58% inertinite	Describe a sequence of lacustrine mudstones with a high inertinite content, generated by wildfires in the hinterland.
Collinson et al., 2000. Acta Palaeobot. 2 p. 93p.	Wealden	Hauterivian to Barremian	Isle of Wight	Charcoal	2 assemblages, charred wood from the Wessex Fm. Mudstones at Hanover Point and charred fern assemblage from the overlying Vectis Fm. and Shepherds Chine
Drinnan et al., 1990. Bot. Gaz. 151 p. 370	Mid Cretaceous	early Cenomanian	E. N. America (Potoniac Group)	Charcoal	Charred flowers
Eklund H et al., 2004. Cretaceous Research 25 p. 211	Late Cretaceous	Late Santonian	Table Nunatak, Antarctica	Charcoal	Charred and structurally preserved plant remains recovered
Falcon-Lang 2004. Palaeontology 47 p. 349	Upper Cretaceous	mid to late Cenomanian	Peruc-Korycany Formation at Pecinov Quarry, near Prague, Czech Republic	Charcoal	Eighteen branch specimens, anatomically preserved as charcoal, the product of wildfire, occur as allochthonous assemblages in intertidal facies and as parauthochthonous assemblages in supratidal salt marsh facies
Falcon-Lang et al., 2007. Can. J. Earth Sci. 44 p. 619	Lower Cretaceous	Valanginian-Hauterivian (140-130 Ma)	Windsor, Nova Scotia	Charcoal	Abundant charcoal found throughout section

Falcon-Lang, 2004. Palaeogeog. Palaeoclim. Palaeoecol. 212 p. 45	Late Cretaceous	Campanian-Maastrichrian (probably Maastrichtian)	NW Ellesmere Island, Canada	Charcoal	Abundant charcoal remains indicate that an additional important disturbance process was wildfire
Finkelstein et al., 2005. Sedimentology 52 p. 587	Late Cretaceous	Campanian - 80ma	Fort Crittenden Fm. S.E. Arizona, USA	PAHs	Pyrolitic PAH and fusinite found. High pyrolitic PAH concentrations in the Fort Crittenden Fm exceed modern background by orders of magnitude and reflect localized or regional wildfires.
Francis, 1984. Palaeogeog. Palaeoclim. Palaeoecol. 48 p. 285	Latest Jurassic	Purbeckian -~147	Purbeck S. England	Charcoal	Charred twigs and shoots but no charred stumps or logs suggesting the fires past quickly through the undergrowth.
Friis 1983 Rev. Palaeobot. Palynol. 39 p. 161	Upper Cretaceous,	Senonian	Sweden	Charcoal	Charred flowers
Friis et al., 1992. Biol. Skr Dansk Vid Selsk 41 p. 1	Late Cretaceous		Portugal	Charcoal	Charred flowers
Friis et al., 1994. Plant Syst. Evol. 8 p. 31	Early Cretaceous		Portugal	Charcoal	Charred flowers
Friis et al., 2000. Int. J. Plant. Sci. 161 p. 772	Early Cretaceous	Barremian or Aptian	Portugal	Charcoal	Charred flowers
Frumin & Friis, 1996. Rev. Of Paleaobot and Palynol. 94 p. 39	Late Cretaceous	Cenomanian-Turonian	Kazakhstan	Charcoal	Charred flowers and seeds
Frumin & Friis, 1996. Rev. Of Paleaobot and Palynol. 94 p. 39	Late Cretaceous	Campanian	North Carolina, USA	Charcoal	Charred flowers and seeds
Goldring 1999. Neues Jahrbuch fur geologie und palaontologie-abgandlungen, 214 p. 67	Lower Cretaceous	Aptian	Fuller Earth, southern England	Charcoal	Including rare grains of quartz, glauconite, sponge spicules, charcoal

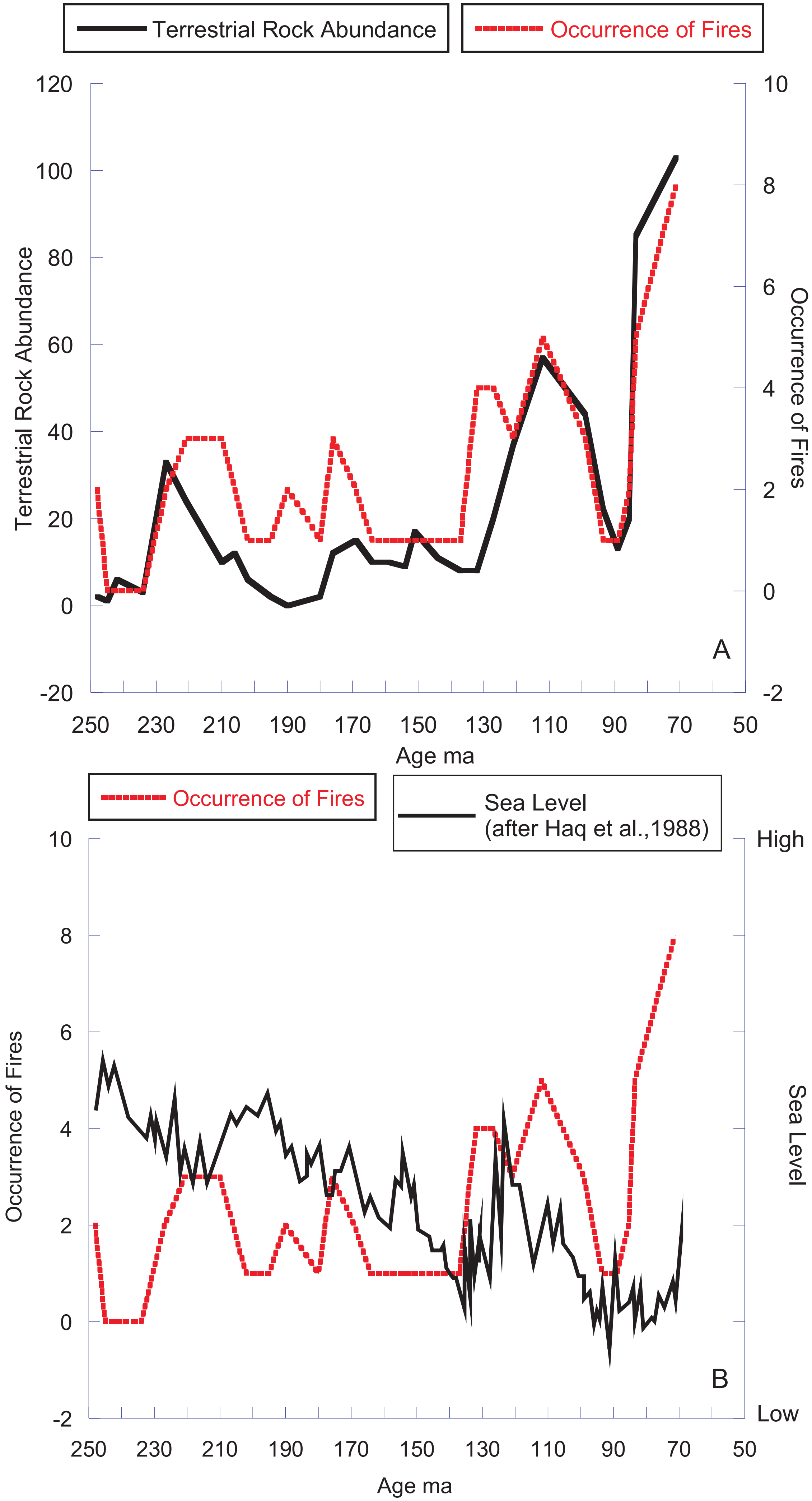
Grocke et al., 2006. Geology, 34 p. 193	Early-Late Cretaceous - 99ma	Late Albian-Early Cenomanian	Dakata Fm. Western Interior Basin, USA	Charcoal	Charcoal occurs throughout the section (used it for $\delta^{13}C$ measurements)
Harris and Rest, 1963. Geological Magazine 103	Late Jurassic	Kimmeridgian	Sutherland, Scotland	Charcoal	Charcoal found
Harris, 1958. The Journal of Ecology 46 p. 447	Lower Lias	Rhaetic (208ma) and lower Lias	E. Greenland	Charcoal	Fusain is abundant, widespread, occurring through great thicknesses of rock in nearly every outcrop
Harris, 1958. The Journal of Ecology 46 p. 447	Middle Jurassic	lower Oolitic	Yorkshire	Charcoal	Fusain is abundant, widespread, occurring through great thicknesses of rock in nearly every outcrop
Harris, 1958. The Journal of Ecology 46 p. 447	Rhaetian	Rhaetian	E. Greenland	Charcoal	Fusain is abundant, widespread, occurring through great thicknesses of rock in nearly every outcrop
Harris, 1958. The Journal of Ecology 46 p. 447	Rhaetian/basal Lias	Rhaetian/basal Lias	S. Wales	Charcoal	Small amount of charcoal
Harris, 1981. Proc. Geol. Assoc. 92 p. 47	Wealden	Barremian?	England, Bearce Brickpit, Surrey	Charcoal	Widespread occurrence of charred ferns
Herendeen & Skog, 1998 J. Plant Sci. 159 p. 870	Lower Cretaceous	Hauterivian-Barremian (127ma)	Bedfordshire UK	Charcoal	Charred ferns found in shallow marine deposits
Herendeen et al., 1999. Ann. Mo. Bot. Gard 86 p. 407	Late Cretaceous	Late Santonian	Allon Flora, Central Georgia, USA	Charcoal	Charred flowers
Jarzembowski, 2003. Acta Zoologica Cracoviensia 46 p. 25	Early Cretaceous	Hauterivian	Lower Weald Clay, English Weald	Charred insects	Insect remains preserved as fusain

Jiang et al., 1998. Organic Geochem. 29 p. 1721	Early Jurassic	Earliest Jurassic	Northern Carnarvon Basin, Western Australia	PAHs	Combustion markers are at low levels, indicating sparse combustion in the terrestrial environment
Jiang et al., 1998. Organic Geochem. 29 p. 1721	Late Triassic	Carnian Norian - 221ma	Northern Carnarvon Basin, Western Australia	PAHs	PAH from wildfires - very abundant combustion-derived PAHs occur in this interval of sediments, suggesting that frequent periodic forest fires and/or swamp/peat fires took place
Jiang et al., 1998. Organic Geochem. 29 p. 1721	Late Triassic	Rhaetian -208ma	Northern Carnarvon Basin, Western Australia	PAHs	The abundances of combustion markers started decreasing steadily and reached low levels by the end of the Triassic, implying a decreasing frequency of forest fires and/or swamp/peat fires
Jones, 1997. TNO 58 p. 93	Middle Jurassic		N. Sea Brent Fm.	charcoal	Numerous charcoal horizons
Jones, Ash and Figueiral, 2002. Palaeogeog. Palaeoclim. Palaeoecol., 188 p. 127	Late Triassic	Late Carnian- Early Norian	Arizona	present	Low abundance of charcoal when compared to the amount of research done in the petrified forest Arizona (no actual abundance data given)
Kalkreuth et al., 1991. Int. J. Coal Geol. 19 p. 21	Lower Cretaceous,	Mid Albian	Gates Fm. British Colombia, Canada	Inertinite content of coals ~20% but up to 40%	Fusain widely reported from coals reaching up to 40% in some horizons
Keller et al., 1996. Am. J. Bot. 83 p. 21	Late Cretaceous	Campanian	Buffalo Creek Member of the Gaillard Formation in central Georgia, USA	charcoal	Fossil flowers, which are exquisitely preserved as charcoal,
Killops & Massoud, 1992. Organic Geochem. 18 p. 1	Upper Jurassic		Korea Bay Basin	PAHs and charcoal	An Upper Jurassic succession of lacustrine mudstones, representing a prograding delta (ca 500 m thick), in Korea Bay Basin was found to contain a range of non-alkylated PAHs typical of pyrolytic origins. The source of this input is probably periodic vegetation fires. The highest levels of pyrolytic PAHs (ca 25 ppm) were recorded for samples which were found to contain fusinite and semi-fusinite, proposed products

					of vegetation combustion.
Lamberson et al., 1996. Palaeogeog. Palaeoclim. Palaeoecol. 120 p. 235	Mid Cretaceous	Mid Albian	Gates Formation, Rocky Mountain Foothills, northeastern British	Charcoal	Inertinite in coal seams
Lubkin, 2003. Acta Zoologica Cracoviensia 46 p. 189	Late Cretaceous	Turonian	Raritan Formation, New Jersey, USA	Charred insect head	Well preserved charred fossil insect head
Mangerud & Romuld, 1991. Rev. Palaeobot. Palynol. 70 p. 199	Middle Triassic	Upper Spathian to Middle Anisian - 240ma	Svalis Dome, Barents Sea	Charcoal	Charcoal found
McElwain et al., 2005. Nature, 435 p. 479	Early Jurassic	Toarcian	SW Bornholm, Denmark	Charcoal	Charcoalified leaf mesofossils
Morgans et al., 1999. Palaios 14 p. 261	Middle Jurassic	Aalenian-Bajocian-bathonian	Ravenscar group, Cleveland Basin, England	Charcoal	Charred wood found throughout the sequence (and imparticular in Aalenian, Bajocian and Bathonian).
Personal Observation of CMB	Triassic-Jurassic Boundary	Triassic-Jurassic	Bed 5 Astartekloft, Greenland	Charcoal	Pieces of charcoal picked from different horizons within plant bed 5 of McElwain et al., 2007. Paleobiology, 33
Petersen & Andsbjerg, 1996. Sed. Geol. 106 p. 259	Middle Jurassic	Bathonian-Callovian	N. Sea Bryne Fm. Central graben	Coals contain up to 60% inertinite	Coals yield abundant charcoal, concluding that there were high frequency fires in the mire systems
Petersen et al., 2003. Geol. Surv. Denmark and Greenland Bull. 1 p. 631	Lower Jurassic	Toarcian	Sorthat Fm. Bornholm	Inertinite	Seam 5 (of the Sorthat Fm.) contains a high proportion of inertinite

Petersen et al., 2003. Geol. Surv. Denmark and Greenland Bull. 1 p. 631	Middle Jurassic	Bathonian	Bag Fm. Bornholm	Fusinite	Fig 8. D - pyrite precipitated in cell lumens in fusinite
Petersen et al., 2003. Geol. Surv. Denmark and Greenland Bull. 1 p. 631	Lower Jurassic	Hettangian-Sinemurian	Sose Bugt Mem. Bornholm	Inertinite	The coaly mustones are inertinite rich
Petersen et al., 2003. Geol. Surv. Denmark and Greenland Bull. 1 p. 631	Middle Jurassic	Bajocian-Bathonian	Haldger Sand Fm., Danish Basin	Inertinite	Fredeikshavn Well-3 contains inertinite
Pole & Douglas, 1999. Cretaceous Research, 20 p. 523	Mid Cretaceous	Late Albian-Cenomanian	Eromanga Basin, central Queensland, Australia	Charcoal	Bennettitales showed a correlation with the presence of charcoal (suggesting fire-tolerance or pioneers after burning)
Putz & Taylor, 1996. IAWA Journal 17 p. 77	Middle Triassic	Anisian	Fremouw Peak, Antarctica	Fire scars	Potential fire scars in fossil wood, but no charcoal actually found.
Sachsenhofer et al., 2006. Petroleum Geoscience 12 p. 363	Lower Jurassic	Hettangian	Gresten Formation; Lower Quartzarenite Member, Höflein gas/condensate field, Austria	Inertinite in coal	The Lower quartzite member was deposited in a flood basin with transitions to a delta-plain environment. Coal originated in frequently flooded mires and evolved within an oxygenated and acidic environment. It is inferred from geochemical data that organic matter from aquatic macrophytes and gymnosperms contributed to coal formation. Wildfires were abundant and oxidation of plant remains occurred frequently. This resulted in the formation of dull coal with very high inertinite contents.
Schonenberger, J. et al., 2001. Ann. Bot. (London) 88 p. 436	Cretaceous	Santonian-Campanian	S. Sweden	Charcoal	Charred flowers
Scott & Collinson, 1978. In: W.B. Whalley (Editor), Scanning Electron Microscopy in the Studies of	Middle Jurassic		N. Yorkshire	Charcoal	Well preserved wood charcoal fragments

Sediments. Geoabstracts, Norwich, p. 137					
Scott et al., 1998. GSA abstract vol 30 A36	Early Cretaceous	Aptian-Albian	Nova Scotia	Charcoal	Several thick charcoal rich units apparent
Scott et al., 2000. Palaeogeog. Palaeoclim. Palaeoecol. 164 p. 381	Late Cretaceous	Maastrichtian (latest Cretaceous)	New Mexico	Charcoal	Latest Cretaceous charcoal from Sugarite locality.
Sweet and Cameron., 1991. Can. Int. J. Coal Geol. 19 p. 121	Late Cretaceous	Maastrichtian (latest Cretaceous)	Rock Creek West, Saskatchewan	Charcoal	Latest Cretaceous charcoal from Rock Creek West locality.
Tosolino 2000. PhD thesis University of Melbourne	Early Cretaceous		Otway & Strzelecki groups Victoria, Australia	Charcoal	Plant biofacies containing charcoal
Wang, 2007. Acta Geologica Sinica-English Edtition, 81 p. 16	Early Cretaceous	Albian	Kansas, USA	Charcoal	High temperature as a mechanism for plant cytoplasm preservation in fossils
Zeigler, 2002. GSA abstract 235	Late Triassic	mid-Norian (~210 - 215 Ma)		Charcoal	Fossil vertebrate assemblage associated with a significant amount of charcoal - suggestion catastrophic Late Triassic wildfire
Ziaja & Wcislo-Luraniec,1999. Acta Palaeobotanica Supplementum , 2 p. 257	Lower Jurassic	Lower Liassic	Odrowaz, Poland	Charcoal	Charcoal found


Terrestrial Rock Abundance
Occurrence of Fires
120
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Terrestrial Rock Abundance
Occurrence of Fires
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Sea Level
(after Haq et al.,1988)
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