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Volcanism, impact and mass extinctions: incredible or credible coincidences?☆

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Abstract

Massive continental volcanism and/or bolide impacts are considered by many authors to have caused three major mass extinction events during the last 300 million years: the end-Permian, end-Cretaceous and end-Triassic extinctions. However, re-evaluation of the frequency of bolide impacts and plume-related flood basalt provinces indicates that both types of event occur much more frequently than mass extinctions, and so, *in isolation*, may not be responsible for the largest extinctions. Furthermore, the kill mechanisms associated with either flood basalts or impacts do not appear to be sufficiently powerful to cause worldwide collapse of ecosystems leading to the largest mass extinctions. Contemporaneous flood basalts *and* bolide impact may be prerequisites for the largest mass extinctions. We present a statistical analysis of the probability of coincidence between volcanism and impact, and show that three random coincidences of these events in the last 300 m.y. are likely. No causal relationship between impact and volcanism is necessary. The lesser mass extinctions, on the other hand, may not require juxtaposition of two such catastrophic events; such coincidences occurring on more than three occasions during the last 300 m.y. become increasingly unlikely.

Keywords: Permo–Triassic mass extinction; Cretaceous–Tertiary mass extinction; Triassic–Jurassic mass extinction; Flood basalts; Meteorites; Impacts

1. Introduction

The causes of mass extinctions have been hotly debated, and commonly cited driving factors fall broadly into three groups: bolide impact (Alvarez et al., 1980), flood basalt volcanism (e.g., Rampino and Stothers, 1988) and intrinsic causes such as anoxia or changes in climate or sea level (see Hallam and Wignall (1997) for a review). Until recently, the only mass extinction that was known to have occurred at

☆ Supplementary information, consisting of a compilation of available radiometric dates for 12 continental flood basalt provinces, together with a list of source references, is available as additional files: White and Saunders_CFBages.xls and White and Saunders_CFBreferences.doc.

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the same time as both massive volcanism and a bolide impact was the Cretaceous–Tertiary (K–T) extinction (Alvarez et al., 1980; Courtillot et al., 1986). The majority of geologists accepted this as a straightforward coincidence, although some have put forward models linking impacts with initiation of large-scale magmatism (e.g., Rampino, 1987; Jones et al., 2002).

The K–T impact hypothesis has resulted in searches for evidence of impact at other extinction horizons, and recently there have been reports of impacts at two other stratigraphic boundaries characterised by extinctions and massive volcanism (end Permian: Becker et al., 2001; end Triassic: Olsen et al., 2002a). Three Phanerozoic mass extinctions are thus now reported to be linked temporally with both volcanism and impacts (Fig. 1): the K–T extinction (65 Ma), the Triassic–Jurassic (Tr–J, 200 Ma) extinction and the Permo–Triassic (P–Tr, 250 Ma) extinction. Although the existence of large scale impacts at the Tr–J and P–Tr boundaries has yet to be verified, the possibility has led to an increase in international mass-media reports of impacts causing not only the extinctions, but also the contemporaneous flood basalts.

Here, we take a different standpoint. We propose that the co-occurrence of a meteorite impact and a plume-related continental flood basalt province may be *required* to cause the very largest extinctions. To test the plausibility of this hypothesis, we return to first principles. Published data on the number and duration of flood basalt events in the last 300 million years, and recent frequency-size distributions for meteorite impacts, are combined into a statistical model that predicts the probability of random coincidence between flood basalt events and meteorite impacts. The implications of these probabilities for flood basalt generation and mass extinctions are explored. We focus mainly on the K–T, Tr–J and P–Tr extinctions because they are the only extinctions to be recognised

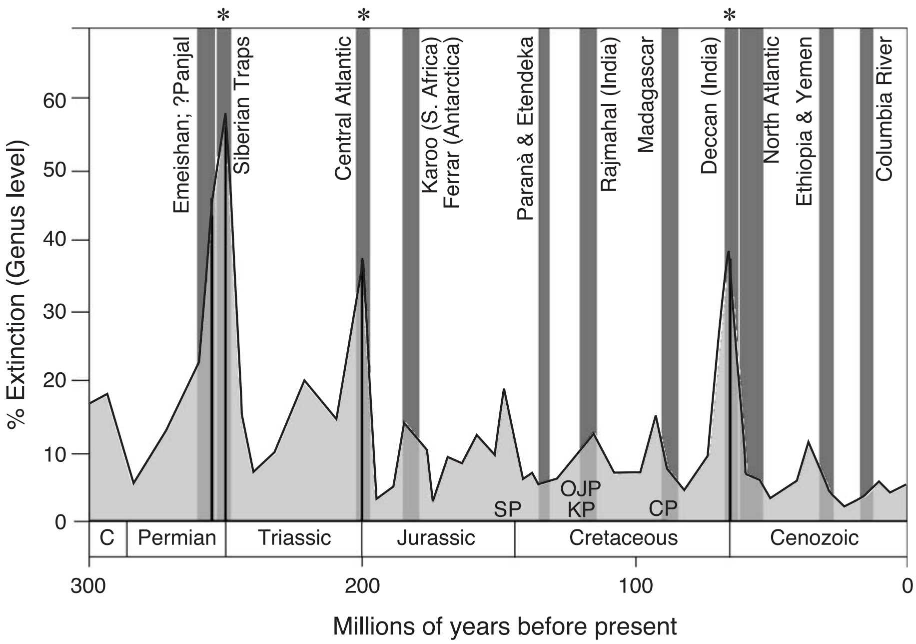

Fig. 1. Extinction rate versus time (multiple-interval marine genera: modified from Sepkoski, (1996) to reflect radiometric age constraints on stratigraphic boundaries) compared with eruption ages of continental flood basalt provinces. Three of the most severe extinctions, the P–Tr, the Tr–J and the K–T, correspond with eruption of the Siberian Traps, Central Atlantic Magmatic Province and Deccan Traps, respectively. Evidence of impact (*) has also been reported at these times (Alvarez et al., 1980; Becker et al., 2001; Olsen et al., 2002a; Basu et al., 2003). The K–T crater is ~180 km in diameter; for the P–Tr and Tr–J boundaries, the size (and indeed existence) of any impact is not confirmed. The end-Guadalupian extinction (~259 Ma) coincides with eruption of the Emeishan Traps (Zhou et al., 2002), but no evidence for impact has been noted for this boundary. Oceanic plateaus may also have had profound environmental consequences (e.g., Kerr, 1998). Selected oceanic plateaus are therefore included on this figure, but as text only, because the preservational bias of the geological record towards younger examples would otherwise render the diagram misleading. SP: Sorachi Plateau, Japan; KP: Kerguelen Plateau; OJP: Ontong Java Plateau; CP: Caribbean-Colombian Plateau.

as major mass extinctions in the compilation of Raup and Sepkoski (1982). It is noted, however, that more recent compilations (e.g., Sepkoski, 1996) show an additional mass extinction at the end-Guadalupian (ca. 259 Ma) that is smaller in magnitude than the P–Tr extinction but larger than the K–T and Tr–J extinctions. The end-Guadalupian extinction is now considered to be a discrete event preceding the end-Permian extinction, but is relatively poorly known or understood (e.g., Erwin, 2002).

2. Extinctions associated with both volcanism and impact?

2.1. Cretaceous–Tertiary

The K–T (65 Ma) mass extinction occurred at the same time as both flood basalt volcanism (Deccan Traps, India: Courtillot et al., 1986) and meteorite impact — a ~10-km bolide that left a worldwide iridium anomaly (Alvarez et al., 1980). The theory that the impact caused the K–T extinction gained credence with the discovery of a 65-m.y.-old impact crater, ~180 km in diameter, at Chicxulub, Mexico (Hildebrand et al., 1991, 1995). Although the relationship of the Chicxulub crater to the K–T boundary impact has been generally accepted for the last decade, there are recent reports that the Chicxulub crater may predate the K–T boundary by 300 kyr, and that another impactor may have been responsible for the extinction (Keller et al., 2002). The crater for this other proposed impactor is not known, but to explain the observed K–T iridium anomaly, it would be expected to be similar in size to the Chicxulub crater.

Realistic 'kill mechanisms' for both meteorite impact and flood basalt magmatism are difficult to prove, and thus the relative influences of these two events on the K–T extinction are still debated (e.g., Wignall, 2001). The fossil record does provide many clues, for example, the existence of disaster/opportunist planktonic foraminiferal assemblages in the Late Maastrichtian points to high stress conditions preceding the impact and the abrupt extinctions at the K–T boundary (Keller, 2003). These high stress conditions correlate temporally with periods of intense Deccan volcanism and were characterised by toxicity and low oxygen due to eutrophication. Stable isotope studies demonstrate abrupt warming (~2–3 °C) of Late Maastrichtian intermediate ocean waters (Li and Keller, 1998), probably linked to increased atmospheric pCO_2. This global warming, which may have been caused by the Deccan volcanism, would have increased weathering and runoff, providing increased flux of biolimiting elements into the oceans, a mechanism that would have contributed to the eutrophication and low oxygen. Hence, it appears that, in the case of the K–T extinction, there is good evidence for volcanically induced biotic stress that was compounded by a meteorite impact.

2.2. Triassic–Jurassic

The eruption of the 200-m.y.-old Central Atlantic Magmatic Province (CAMP) happened at the same time, within analytical error, as marine Tr–J extinctions (Marzoli et al., 1999; Pálfy et al., 2000). Early searches for iridium anomalies (Orth et al., 1990) and shocked quartz were negative or ambiguous (Bice et al., 1992; Hallam, 1990), but recent results from the terrestrial Newark basin demonstrate a small iridium anomaly (maximum of 285 ppt: Olsen et al., 2002a). This compares to a value of 6300 ppt from the Gubbio K–T boundary section (Alvarez et al., 1980). Thus, any Tr–J impactor, if confirmed, is likely to be considerably smaller than the K–T meteorite.

Moreover, there is some ambiguity about whether the Ir at the Tr–J boundary has an extra-terrestrial or terrestrial provenance. Olsen et al. (2002b) used the lack of correlation between Ir and elements such as Cs, Al, Cu and V to suggest that a volcanic origin for the Ir was unlikely. A different picture emerges when considering elements such as Ni, Cr and Ir, which may provide useful diagnostic tools for evaluating whether sedimentary rocks have volcaniclastic and/or extra-terrestrial material incorporated within them (Kerr, 1998).

In Fig. 2, Cr/Ir is plotted against Ni/Ir for a range of terrestrial rocks and chondritic meteorites. The range of Ni/Ir spans over four orders of magnitude, from chondritic meteorites with low Ni/Ir (generally $<3\times10^4$) to mid-ocean-ridge basalts that may have Ni/Ir exceeding 1000×10^4. Plume-related basalts (e.g., Iceland, Réunion), large igneous provinces (e.g., Central Atlantic Magmatic Province, Ontong Java Plateau, Siberian Traps) and komatiites have

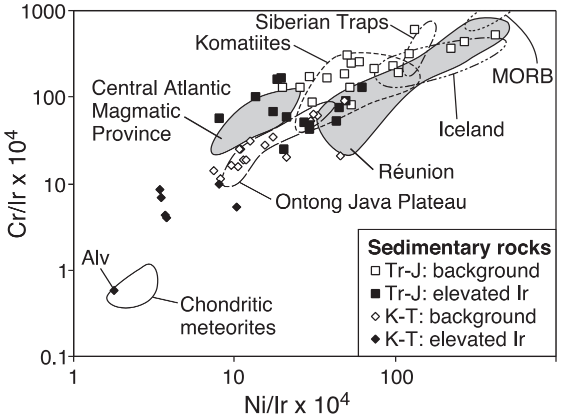

Fig. 2. Cr/Ir vs. Ni/Ir abundance ratios in a range of terrestrial igneous rocks and chondritic meteorites, compared with sedimentary rocks spanning the K–T and Tr–J boundaries. Data sources: chondritic meteorites: Wasson and Kallemeyn (1988); Ontong Java Plateau (ODP Leg 192): Chazey and Neal (2004); Central Atlantic Magmatic Province (Western Newark Basin intrusives): Gottfried et al. (1991); Siberian Traps: Lightfoot et al. (1990) and Brügmann et al. (1993); komatiites: Brügmann et al. (1987) and Rehkämper et al. (1999); Reunion (ODP Leg 115): Fryer and Greenough (1992); Iceland: Rehkämper et al. (1999); MORB: Rehkämper et al. (1999). K–T boundary sedimentary rocks: point marked Alv from Alvarez et al. (1980); all others from Stüben et al. (2002) where 'elevated Ir' samples belong to MU3 anomaly and have Ir of 0.5–1 ppb. Tr–J boundary sedimentary rocks are from Olsen et al. (2002a); 'elevated Ir' are those samples with Ir of 0.08–0.29 ppb. 'Background' samples from both sections are included for comparison.

intermediate Ni/Ir and Cr/Ir values (from ~10×10^4 to ~500×10^4).

Sedimentary rocks from key sections such as the K–T boundary (Alvarez et al., 1980; Stüben et al., 2002) have Ni/Ir and Cr/Ir ratios that are lower than any known terrestrial igneous rocks (Fig. 2), which can only be explained by a significant extra-terrestrial component. In contrast, samples spanning the Tr–J boundary in the Newark Basin neither require nor rule out an extra-terrestrial component. The samples with elevated Ir do have lower Ni/Ir and Cr/Ir than the background samples, but all samples have Ni/Ir and Cr/Ir ratios that fall within the range of terrestrial basaltic rocks, including the nearby CAMP, and so it remains ambiguous whether the source of the high-Ir component is volcanic or extra-terrestrial.

The fossil record at the Tr–J boundary demonstrates that many groups were in decline throughout the late Triassic (Tanner et al., 2004). Some groups appear to have been subject to only regional effects; for example, an abrupt crisis in terrestrial flora (McElwain et al., 1999) has not yet been recognised beyond the North Atlantic region (Hallam and Wignall, 1997). Difficulties in correlation between biostratigraphic and various radiometric dating methods mean that it is not yet clear whether the terrestrial and marine extinctions were synchronous (e.g., Pálfy et al., 2000). Palaeoclimate interpretations are ambiguous: a dramatic increase in atmospheric pCO_2 inferred from stomatal density analysis (McElwain et al., 1999) appears to conflict with isotopic data from palaeosols (Tanner et al., 2004). A carbon isotope shift hints at the involvement of methane hydrates, but in general, the fossil record does not appear to tell a story of a single catastrophic event (Tanner et al., 2004).

2.3. Permo–Triassic

The P–Tr extinction (~250 Ma) was contemporaneous with large scale volcanism of the Siberian Traps (Renne et al., 1995) and the adjacent West Siberian Basin (Reichow et al., 2002). A contemporaneous large bolide impact has been proposed, based on P–Tr boundary fullerenes containing trapped noble gases with isotopic ratios indicative of an extraterrestrial source (Becker et al., 2001). These results are controversial (Farley and Mukhopadhyay, 2001; Braun et al., 2001), and other claims for an P–Tr impact (Kaiho et al., 2001; Xu et al., 1985) have also been disputed (Koeberl et al., 2002; Zhou and Kyte, 1988). There has been a recent report of a possible end-Permian impact structure, the Bedout High, located on the northwestern continental margin of Australia (Becker et al., 2004), but experts on shock metamorphism have not yet been convinced by the evidence presented (Kerr, 2004). Searches for indicators such as shocked quartz at the P–Tr boundary have turned up the 'scent' of an impact (i.e., smaller and much less abundant shocked quartz grains than the K–T boundary: Retallack et al., 1998), and magnetic silicate aggregates interpreted as chondritic meteorite fragments and iron-rich metallic grains are associated with the P–Tr boundary in Antarctica (Basu et al., 2003).

It seems, therefore, that an impact at the P–Tr boundary remains a possibility. Nonetheless, the size of such an impact remains poorly constrained. The suspected Antarctic chondritic meteorite fragments are not associated with significant Ir anomalies, which

Basu et al. (2003) note may be because the Ir is not concentrated in a thin layer, as it is at the K–T boundary. However, even assuming that their magnetic fraction is entirely bolide-derived, and that the concentration of metallic fragments remains constant throughout the entire 25-cm bed thickness, the maximum impactor diameter would be ~8 km. A similar calculation for sediment containing metallic grains from the 4-cm P–Tr bed at Meishan (China) yields an impactor diameter of ~3 km. (These calculations use the same assumptions as Alvarez et al., 1980 relating to chondritic Ir abundances and proportion of impacting material that is eventually preserved in fallout sediments.)

The geological record of the P–Tr boundary shows a rapid marine extinction (Bowring et al., 1998; Jin et al., 2000) with epifaunal suspension feeders faring worse than more mobile groups (Erwin et al., 2002). On land, vertebrates, insects and plants suffered, and the widespread presence of apparent fungal remains (Visscher et al., 1996) demonstrates the global nature of the extinction event. Marine anoxia was extensive (Wignall and Twitchett, 1996), and a marked negative carbon isotope shift present at the boundary in both marine and terrestrial sediments (e.g., Baud et al., 1989; Thackeray et al., 1990; Morante, 1996) may be indicative of methane hydrate involvement. Although the extinctions appear to have been rapid, they did occur during a period of global warming: warm-water algae migrated to higher latitudes by the Early Triassic (Wignall et al., 1998), cold-adapted terrestrial flora were badly affected (Retallack, 1995) and the oxygen isotope record of tropical carbonates implies a global temperature increase of ~6 °C (Holser et al., 1991). Thus, like the K–T extinction, the P–Tr record appears to record a story of rapid extinctions occurring during a period of global warming.

3. Statistical calculations

Assuming that there is no direct causal link between impact and volcanism (see later), a single coincidence between flood basalt volcanism and bolide impact during the last 300 m.y. (i.e., at the K–T boundary) is believable. Even though both flood basalts and impacts are relatively common geological phenomena, invoking multiple coincidences to explain other mass extinction events becomes less credible. We therefore present a straightforward statistical model that examines the probability of coincidences between randomly occurring impacts and flood basalt volcanism. Results are presented in Table 1 and Fig. 3. The model considers only the probability of coincidence with a continental volcanic province, because subaerial eruptions have the greatest potential for wreaking environmental havoc (Rampino et al., 1988), and it is continental flood basalts that have been observed to correlate temporally with some of the larger mass extinctions (e.g., Wignall, 2001) (Fig. 1).

Oceanic large igneous provinces may also have had serious environmental consequences and some do coincide with extinctions (e.g., Kerr, 1998). If oceanic large igneous provinces were included in the statistical calculations, the probabilities of coincidence would be higher. However, inclusion of oceanic provinces

Table 1
Probabilities of coincidence between impact craters and the 12 continental flood basalts of the last 300 million years

Min. crater size (km)	Average flood basalt duration (Ma)				
	0.5	1	2	3	5
Probability (%) of one or more coincidences					
30	99.92	100	100	100	100
60	82.8	97.1	99.93	99.999	100
100	46.5	71.8	92.5	98.1	99.90
140	27.6	48.0	73.7	87.1	97.2
180	18.3	33.5	56.6	72.1	89.3
Probability (%) of two or more coincidences					
30	99.33	99.999	100	100	100
60	52.1	86.7	99.39	99.98	100
100	12.7	35.4	72.1	90.1	99.13
140	4.0	13.3	37.0	58.8	85.9
180	1.6	5.8	18.8	34.2	62.4
Probability (%) of three or more coincidences					
30	97.2	99.993	100	100	100
60	25.3	68.1	97.4	99.88	100
100	2.4	12.6	45.6	73.6	96.3
140	0.4	2.4	13.1	30.0	64.8
180	0.08	0.6	4.0	10.9	32.2
Probability (%) of four or more coincidences					
30	92.2	99.96	100	100	100
60	9.7	46.1	92.5	99.48	100
100	0.3	3.4	23.3	52.0	89.3
140	0.02	0.32	3.4	11.6	40.2
180	0.003	0.04	0.58	2.4	12.1

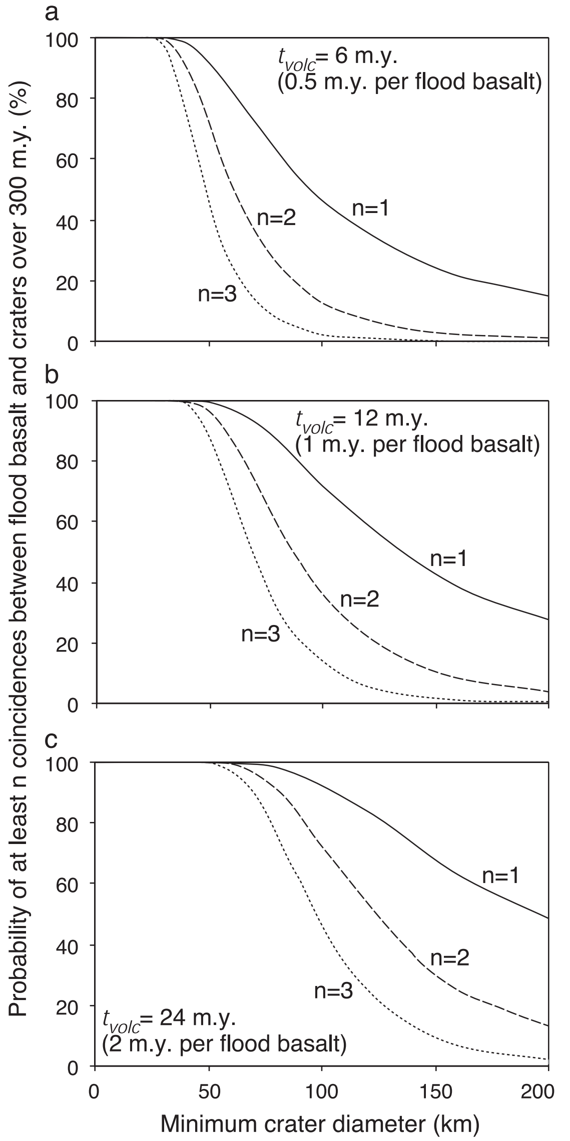

Fig. 3. Results of statistical calculations, presented as the probability (%) of at least n coincidences between randomly occurring impacts and periods when the Earth was affected by flood basalt volcanism, over a 300-m.y. interval. The probability is sensitive to the duration of harmful long-term effects of flood basalt volcanism, so results are presented for average durations of: (a) 0.5 m.y., (b) 1 m.y. and (c) 2 m.y. For smaller crater diameters, at least three coincidences between impacts and flood basalt episodes are inevitable.

would require a set of assumptions to be made about the number of provinces and the duration of their activity, and this is even more poorly constrained than for continental flood basalt provinces, especially for the period prior to 120 Ma. Hence, we do not feel that we can justify the inclusion of oceanic plateaus in the statistical calculations at this stage.

The probability, x, of any single impact coinciding with a period of flood basalt volcanism is related to the total duration of volcanism (t_{volc}) as a fraction of the total time period under consideration (t_{tot}):

$$x = t_{\mathrm{volc}} \div t_{\mathrm{tot}} \tag{1}$$

The number of craters, c, per km^2 per year having a diameter exceeding D (km) is derived from the crater production rate equation (Hughes, 1998):

$$\log c = -11.67 - 2.01 \log D \tag{2}$$

The total expected number of craters, C, larger than diameter D is related to the crater production rate, the total time period under consideration and the surface area of the Earth:

$$C = c \times t_{\mathrm{tot}} \times 5.11 \times 10^8 \ \mathrm{km}^2 \tag{3}$$

The percentage probability (P) of exactly n coincidences between impacts and flood basalt volcanism is given by:

$$P = 100 \times x^n \times (1-x)^{(C-n)} \times C! \div [(C-n)!n!] \tag{4}$$

The percentage probability of at least n coincidences between impacts and flood basalt volcanism is obtained by summing the probabilities from n to n=C:

$$\sum_{n=n}^{n=C} P \tag{5}$$

We believe that the assumption of no causal link between impact and the generation of large igneous provinces is justified on several grounds. Although impacts are known to cause shock melting on a local scale (Melosh, 1989), there are no documented cases on Earth where an impact crater is temporally and spatially related to a large igneous province. For example, there is no large igneous province emanating from the Chicxulub crater, and suggestions that the Deccan flood basalts formed via focusing of seismic waves at the antipode are incorrect—the Deccan Traps were not located directly opposite the Chicxulub impact (Boslough et al., 1996). Moreover, the presence of an iridium anomaly in sediments between lava flows demonstrates that Deccan volcanism began before the end-Cretaceous impact (Bhandari et al., 1995). The mechanism by which impact induces volcanism has also been questioned, as numerical simulations have shown that the most popular type of model, ascribing impact-induced volcanism to voluminous decompression melting beneath the crater (e.g., Jones et al., 2002), is probably incorrect (Ivanov and Melosh, 2003).

3.1. Results

The results of our statistical modelling are strongly dependent on the total duration of flood basalt magmatism and the minimum crater size considered necessary for an impact to have had significant environmental effects (see later). The probabilities of coincidences between flood basalts and randomly occurring impact events in Table 1 and Fig. 3 are thus presented for a range of crater sizes and flood basalt durations.

Using a conservative average value for each flood basalt duration of 2 m.y., at least one coincidence between a flood basalt and a ≥180-km crater (at least K–T-sized impactor) is likely (probability=57%) over a period of 300 million years. The probability of at least two coincidences between flood basalts and Chicxulub-sized impacts is 19%. Three such coincidences become increasingly unlikely (4%).

If the coincident impactors are not required to be as large as the K–T impact, the probabilities increase markedly. For craters exceeding 100 km in diameter, the probability of at least three coincidences between impact and flood basalts increases to 46% and, for craters larger than 60 km, the probability is 97%—almost a certainty. This is illustrated graphically in Fig. 4, which shows results of numerical simulations of randomly timed impacts and flood basalt provinces. This simulation assumes 12 flood basalt events, which are assigned a duration of 2 m.y. each and a random age in the interval 0–300 Ma. The expected number of craters of a particular size range was calculated from Eq. (2). Each crater was then assigned a random age in the interval 0–300 Ma and a random size within the appropriate range. The size ranges used were >300 km, <20 km and 16 other 'bins' covering the interval

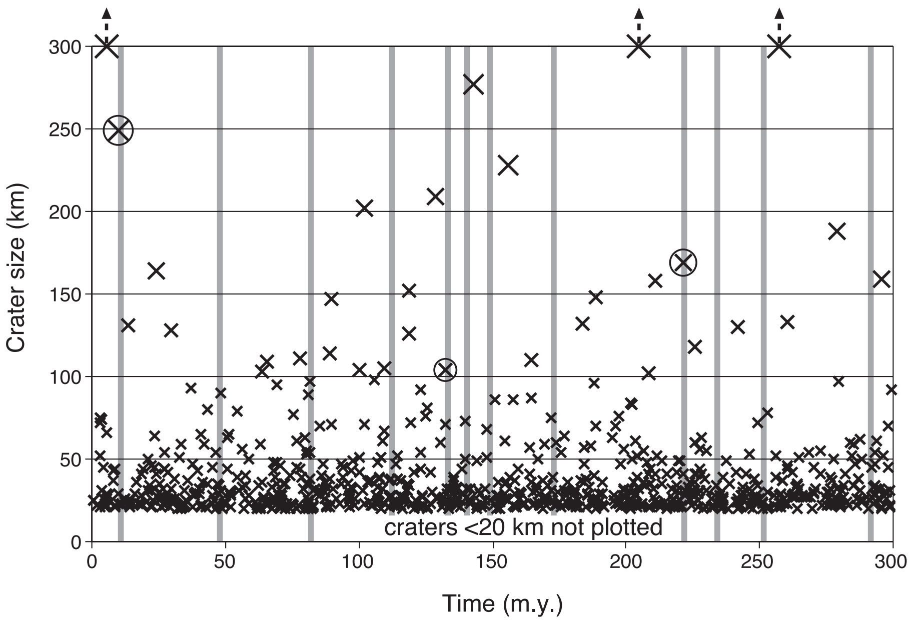

Fig. 4. Example of numerical simulation demonstrating the likelihood of coincidence between randomly timed impacts and flood basalt events. The sizes and frequencies of craters are constrained to fit the distribution expected from the crater production rate equation of Hughes (1998). The number of flood basalt events is set at 12, to match the observed record since 300 Ma; the duration of flood basalt episodes is set arbitrarily at 2 million years. Large impact events that coincide with flood basalt events are circled.

between 20 and 300 km. The aim of the large number of bins was to minimise any bias towards larger impacts when allocating random sizes within each bin. In the particular simulation illustrated in Fig. 4, three craters, with diameters of 250, 170 and 105 km, coincide with flood basalt events.

3.2. Crater production rates

The principal uncertainty in this statistical analysis is our knowledge of the expected distribution of different sized impact events through geological time. Estimates of crater production rates are based on the abundance of known craters on Earth and the observation of Earth-crossing asteroids. If reasonable asteroid impact velocities are assumed, the crater produced by impact is approximately 20 times the diameter of the impactor (French, 1998).

The equation selected for our statistical modelling (Hughes, 1998) is equivalent to a production rate of craters with $D \geq 20$ km of $(5.2 \pm 2.4) \times 10^{-15}$ km^2 year^{-1}, which compares favourably with other recent estimates (e.g., $(5.6 \pm 2.8) \times 10^{-15}$ km^2 year^{-1}: Grieve and Shoemaker, 1994) but supercedes older values (e.g., $(2.6 \pm 0.9) \times 10^{-15}$ km^2 year^{-1}: Hughes (1981); $(3.5 \pm 1.3) \times 10^{-15}$ km^2 year^{-1}: Grieve and Dence, 1979). The main reason for the discrepancy between the recent and older estimates is the fact that additional terrestrial craters and Earth-crossing asteroids are continually being discovered (Grieve, 1998) (Fig. 5).

These recent estimates of crater production rates yield an expected mean time between Chicxulub-sized impacts of only ~30 million years, considerably less than the commonly cited 100-m.y. interval. Although Alvarez et al. (1980) also estimated a repeat interval of 30 m.y., they rejected this value in favour of a 'more sophisticated calculation' that yielded 100 m.y.; the latter figure may have been chosen because the 'desire to fit not only the C–T [*sic*] extinction, but earlier ones as well, sets the mean time between extinctions at ~100 m.y.' However, both modelling and observation predict that Chicxulub-sized events should have occurred much more frequently than every 100 m.y. (Wetherill and Shoemaker, 1982; Grieve, 1982; Grieve and Shoemaker, 1994; Hughes, 1998), indicating that not all of them can have caused mass extinctions.

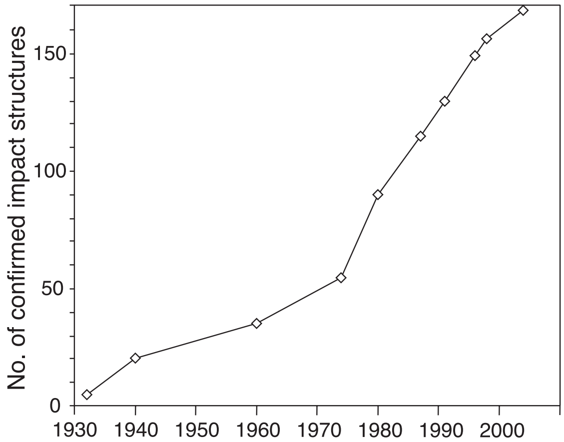

Fig. 5. Variation in cumulative number of confirmed terrestrial impact structures with time, from Grieve (1998), updated to 20 January 2004 using the Earth Impact Database (2004). Note that the total number of craters known increased by approximately 85% between 1980 and 2004.

3.3. Duration of flood basalt magmatism

The probability of randomly occurring impacts coinciding with large igneous provinces is also sensitive to the duration of flood basalt magmatism, which is poorly known and/or controversial for many of the 12 continental flood basalt provinces of the last 300 million years (Fig. 6; Supplementary information). Table 1, therefore, presents probabilities for a number of different scenarios ranging from 0.5 to 5 million years per province (t_{volc}=6–60 m.y.).

Determining the duration of volcanism is hampered by the fact that the ^{40}Ar–^{39}Ar method has insufficient analytical precision to resolve closely spaced events. Where ^{40}Ar–^{39}Ar results are indistinguishable within error, other techniques, such as magnetostratigraphy, can be employed. However, this requires the correct assignation of rock units to magnetic polarity intervals, which can be problematic, especially for pre-Cretaceous rocks (compare Westphal et al., 1998 with Reichow et al., 2002), but is more straightforward for younger rocks that are also precisely dated by radiometric methods (e.g., Chambers and Pringle, 2001).

Possibly the best documented example is the Deccan Traps, for which a minimum duration of 0.6 m.y. was suggested, based on the majority of magmatism occurring in Chrons 30N-29R-29N (Courtillot et al., 1986). However, subsequent refinement of the geomagnetic reversal time scale

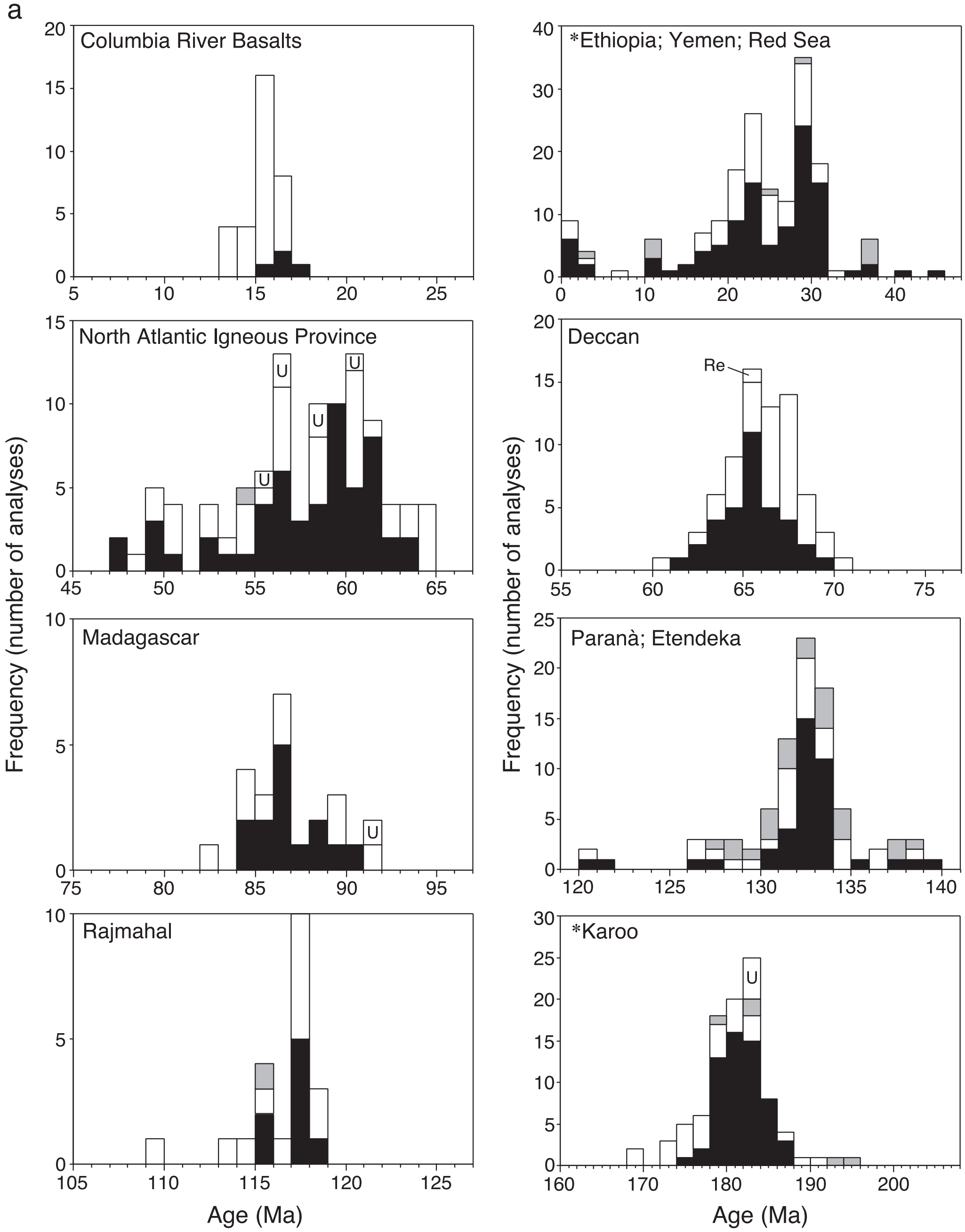

Fig. 6. Summary of available radiometric data for continental large igneous provinces. Where appropriate, $^{40}Ar–^{39}Ar$ data are recalculated and reported relative to 98.79 Ma for biotite standard GA1550 (Renne et al., 1998). Histograms do not necessarily reflect proportion of magmas generated at these times, as they are prone to sampling biases. Black represents $^{40}Ar–^{39}Ar$ data that conform to certain quality criteria (i.e., carried out by multi-step heating resulting in long contiguous plateaus, ages reported relative to a well characterized standard, plateau ages within error of isochron ages (where reported), and isochrons with atmospheric intercepts); white is $^{40}Ar–^{39}Ar$ data that do not meet the strict criteria above; grey is total fusion $^{40}Ar–^{39}Ar$ data. U: uranium–lead data. Re: Re–Os data. *Karoo and Ethiopia have a condensed horizontal scale. No radiometric data are available for the Panjal province; the stratigraphic age is Kungurian–Artinskian (~275–258 Ma).

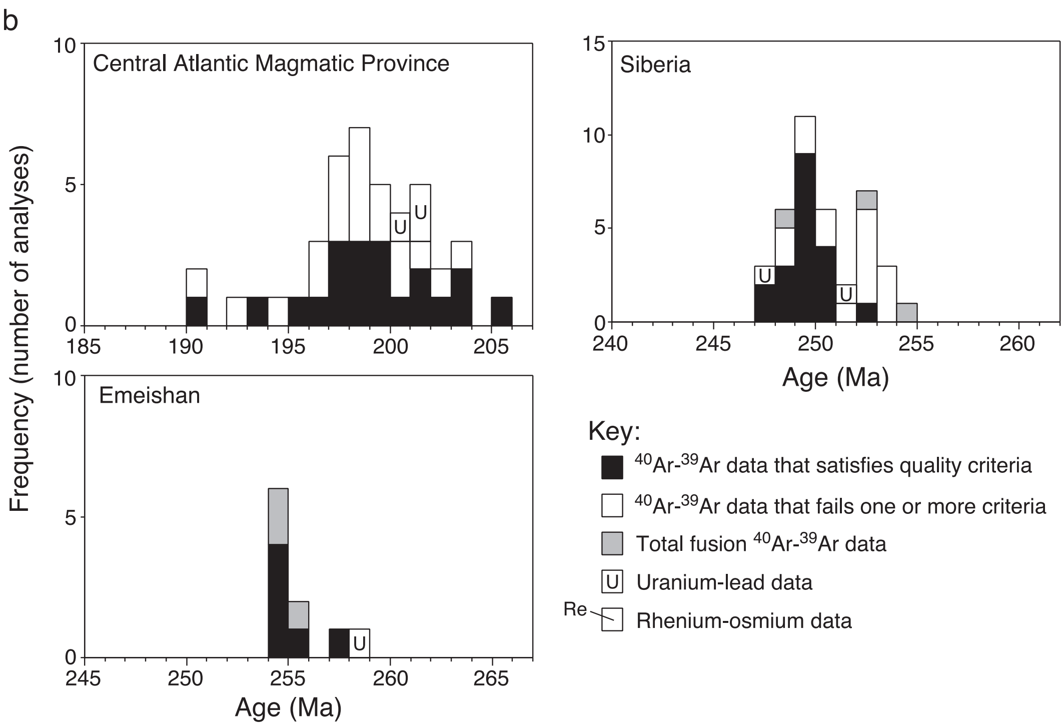

Fig. 6 (*continued*).

(Cande and Kent, 1995) indicates that Chron 29R lasted ~0.8 m.y., implying a minimum duration of ~1 m.y. for the main Deccan volcanism. Moreover, there are notable cases where $^{40}Ar–^{39}Ar$ studies covering larger geographic or stratigraphic ranges have demonstrated that magmatism continued over longer intervals, e.g., at least 1–2 m.y. after the K–T boundary for the Deccan province (Widdowson et al., 2000). Some provinces, e.g., Paranà–Etendeka, may have erupted over even longer intervals of up to 10 m.y. (Turner et al., 1994).

Volcanic provinces that were active at the same time and originally contiguous (e.g., Paranà and Etendeka) are treated as one province for the purposes of the statistical modelling. Provinces that may be similar in age but are geographically distinct are treated separately (e.g., Siberia, Emeishan, Panjal). Any overlap in the timing of volcanism in these regions will lead to an overestimate of t_{volc} and overestimate the probability of an impact-basalt coincidence. Our statistical model does not include oceanic large igneous provinces, as their submarine volcanic activity is considered to have had less significant environmental effects. However, some oceanic large igneous provinces also had a subaerial component (e.g., Ontong Java: White et al., 2004; Kerguelen: Frey et al., 2000; Caribbean: White et al., 1999); if these provinces were included, t_{volc} and the probability of an impact-basalt coincidence would both be higher.

4. Single causes for mass extinctions?

4.1. Flood basalt volcanism

Although the arguments for correlations between extinctions and some flood basalt events are compelling (e.g., Wignall, 2001), it should be noted that there are many more flood basalt events in the geological record than there are significant mass extinctions, implying that continental flood basalt provinces may not, on their own, cause mass extinctions. The greatest problem for advocates of the flood basalt theory as a cause of mass extinctions is the lack of a credible catastrophic kill mechanism.

That the biosphere can be disrupted by volcanism is not in doubt — Mount Pinatubo's 1991 eruption was sufficiently explosive to cause a drop in global temperatures via the injection of volcanic ash and sulphate aerosols into the stratosphere (McCormick et al., 1995), and the 1783 eruption of Laki in Iceland caused famine and may have contributed to an extremely cold winter (Thordarson and Self, 2003; Grattan, 2005). However, sulphate aerosols only have a residence time of a few years in the stratosphere (Rampino et al., 1988), and the real question is whether this short-term cooling would have been enough to weaken ecosystems to such an extent that extinctions would occur. Even though the largest flood basalt eruptions may have lasted a decade or more (Thordarson and Self, 1996), and continuously replenished atmospheric sulphate aerosols during that period, the intervals of repose between emplacement of individual flows could have lasted centuries, or even millennia, depending on the overall duration of the flood basalt province and the total number of flows. These prolonged intervals of tranquillity should have allowed ecosystems to recover.

One factor that might contribute to the proposed damaging effects of flood basalt provinces is the suggestion that the short-term volcanic cooling episodes were superimposed on a long-term trend of volcanically induced global warming. CO_2 is produced in prodigious quantities by flood basalt magmas and has a much longer residence time in the atmosphere than sulphate aerosols. For example, assuming a volume of 2.3×10^6 km^3 (Reichow et al., 2002) and degassing of 0.6 wt.% CO_2, the Siberian Traps would have released 11,000 Gt of carbon (GtC). This sounds like an enormous amount compared to the current atmospheric reservoir of ~750 GtC, but the flux is actually small (0.006 Gt year^{-1} averaged over 2 m.y.) in comparison to the modern anthropogenic output of ~7 GtC year^{-1}. Berner (2002) modelled the release of CO_2 from volcanism occurring over a period of 200 kyr, and concluded that flood basalt volcanism would probably lead to an approximate doubling of atmospheric CO_2 (which would lead to a global temperature increase of 1.5–4.5 °C at the present day: Houghton et al., 2001). Flood basalt provinces would, however, have been active over periods considerably longer than 200 kyr, and this protracted carbon release is likely to have been more effectively buffered by Earth's feedback mechanisms. Another possible scenario to consider is that the repeated 'volcanic winters' were severe enough to reduce viability of ecosystems to such an extent that the fall in productivity adversely affected Earth's CO_2 drawdown mechanisms.

It may be that there are other volcanically driven environmental stress factors that require further study. For example, sulphate aerosols that accumulate in the troposphere rather than the stratosphere cause a vertical redistribution of solar radiation between the surface and the lower atmosphere, i.e., the surface cools and the lower troposphere warms, leading to a weaker hydrological cycle, suppression of rainfall, and less efficient removal of pollutants (Ramanathan et al., 2001). If the distribution of sulphate aerosols from a flood basalt eruption was localised in the troposphere of one hemisphere, it could have profound effects on ocean circulation systems. Nevertheless, it is difficult to see how long-term flood basalt eruptions can have sufficiently catastrophic effects to be the sole cause of mass extinctions.

It should be stressed, however, that the correlations in timing between flood basalt eruptions and the three major mass extinctions of the last 300 Ma are persuasive. Our statistical model can also be applied to coincidences between flood basalts and mass extinctions, assuming no causal links and random timing of both types of event. Assuming 12 flood basalts with a mean duration of 2 m.y., as before, the probability of exactly 3 coincidences between flood basalts and the 3 large mass extinction events is 0.05%. Put another way, the odds of these three mass extinctions *not* being somehow causally linked to flood basalt eruptions are 2000 to 1. This strongly suggests that flood basalts were a contributory factor in the K–T, Tr–J and P–Tr extinctions, even if they were not the sole cause. Include a fourth coincidence—between the end-Guadalupian extinction and the Emeishan flood basalt province—and the odds of mass extinctions *not* being causally linked to flood basalt eruptions plummet to 24400 to 1.

4.2. Impact

Scenarios painted by advocates of impact-extinction theories are satisfyingly catastrophic. Alvarez et al. (1980) depicted a scene involving impact-derived dust that prevented sunlight from reaching the Earth's surface for several years, suppressing photosynthesis and causing food chains to collapse. This portrayal has been challenged by Pope (2002), who stated that the amount of submicrometer-size dust in the K–T ejecta layer is two to three orders of magnitude less than that needed to shut down photosynthesis. Alternative kill mechanisms include global cooling from sulphate aerosols (e.g., Pope et al., 1997) and soot from global wildfires (e.g., Wolbach et al., 1990) ignited by the thermal power delivered by the impact. However, the sulphate aerosol mechanism requires an impact on sulphate-bearing target rock, which works for the K–T extinction (assuming that Chicxulub is indeed the causative impact site), but is unlikely to be applicable to other impact events. The global wildfire theory has also been contested, based on the observation of non-charred organic materials from North American K–T boundary sediments (Belcher et al., 2003).

The fact that kill mechanisms remain a subject for debate, even for a well documented meteorite impact, means that the story is not as clear cut as was previously thought, and even catastrophic events such as meteorite impacts may not be capable of causing mass extinctions without other contributory factors. If the more recent cratering statistics are correct, and the anticipated repeat interval of a Chicxulub-sized impactor is only 30 m.y., then large impacts are much more frequent than major mass extinctions, and it is evident that not all of these large impacts can have caused mass extinctions.

There is further evidence to suggest that impacts, alone, do not cause global extinction events. Hypothesized 'kill curves' (e.g., Raup, 1992) relating percentage extinction rates to crater size do not appear to fit observations (Hallam and Wignall, 1997), probably because they do not take into account other Earth-bound variables. It has been proposed that there is a threshold effect whereby no extinctions occur until the crater is at least 45 km (Jansa et al., 1990) or even 100 km (Poag, 1997) in diameter. However, the expected frequency of these smaller impacts greatly exceeds the number of significant mass extinctions (Fig. 4), which suggests that the threshold size for an impact being the *sole* cause of a mass extinction should be set at a much higher level.

4.3. Mantle-plume induced lithospheric gas explosions

Phipps Morgan et al. (2004) have also noted the apparent coincidences between mass extinctions, flood basalts and impact signals, and calculated that they have occurred far too often in the geological record to be plausibly attributed to random events. Their preferred explanation is a causal link between impact signals and mantle plume activity. However, in contrast to models where extra-terrestrial impact causes flood basalt volcanism (e.g., Jones et al., 2002), Phipps Morgan et al. (2004) propose a mechanism by which mantle plumes impinging on cratonic lithosphere cause both flood basalt eruptions and explosive lithospheric gas release. They suggest that it is these lithospheric gas explosions, rather than extra-terrestrial impactors, that produce shocked quartz, nanodiamonds, microspherules, iridium anomalies and C_{60}–C_{70} fullerenes in the geological record, but acknowledge that the craters may have been caused by impact.

On the basis of the statistical calculations reported in this paper, we disagree that a causal link is required between flood basalts and impact signals. The discrepancy between our reasoning and that of Phipps Morgan et al. (2004) primarily arises because of differences in our starting assumptions. We assume a mean interval of 25 m.y. between flood basalt events compared to their 30-m.y. interval; our preferred flood basalt duration is 2 m.y. compared with 1 m.y. The main difference, however, is that Phipps Morgan et al. (2004) allow only one impact event per 100 m.y., based on the older cratering statistics and the supposition that only Chicxulub-sized impactors are large enough to be significant. Using the more up-to-date cratering statistics (Hughes, 1998), such a long expected interval between impacts would only be achieved for craters >320 km in diameter; thus, it is unsurprising that coincidences between these impacts and flood basalt events are seen as implausible. Moreover, the mathematical method used by Phipps Morgan et al. (2004) to calculate probabilities of coincidence is an oversimplification. Expressed in the terms defined in our paper, their equation simplifies to $(Cx)^n$ (compare with Eq. (5)); this does not take into account the various permutations of coincidence and non-coincidence that become increasingly important as the number of impactors increases.

Resolution of these differences in approach awaits confirmation of the presence of impact markers at the P–Tr and Tr–J boundaries, together with some sort of verification of the size of any impactors (ideally via discovery of craters, if preserved). Only if the presence of large impacts at these boundaries is established, and the impacts are spatially associated with the contemporaneous flood basalts, will we concede that it is worth pursuing models involving causal links between flood basalts and impact markers (either via the mechanism of Jones et al., 2002 or Phipps Morgan et al., 2004). In the meantime, our preferred explanation is that the majority of impact signals found in the geological record result from impact events that were significantly smaller than the Chicxulub impact, a possibility that is also mentioned by Phipps Morgan et al. (2004).

5. Multiple causes for mass extinctions?

Our discussion on the causes of mass extinctions has thus far been oversimplistic, in that it has completely ignored terrestrial factors such as palaeogeography and species distribution, eustatic sea level changes, changes in ocean circulation, oceanic anoxia and global warming related to methane hydrate release. Some of these factors could be consequences of meteorite impact or volcanic activity; others not. A full discussion of these topics, and their interactions, is beyond the scope of the current paper (but see Hallam and Wignall, 1997; White, 2002 for reviews). What is important is that the Earth, and its ecosystems, are continuously evolving and therefore the system will vary in its response to environmental pressures. If meteorite impacts occur during periods of increased ecosystem stress, mass extinctions are more likely to occur than if impacts occur when Earth is in a more robust phase of its development.

5.1. Degree and timing of vulnerability

Intrinsic changes in Earth's susceptibility to mass extinctions are currently too complex to model quantitatively. However, large scale plume-related volcanism will impose additional environmental stresses that increase vulnerability, even if they are not sufficient to cause a mass extinction directly. If further work can quantify the degree and timing of this volcanically induced vulnerability, our statistical model could be modified accordingly. Additional research is therefore needed into the stresses that volcanic activity places on ecosystems, and for this to be achieved, more information is required on the size, volatile budget and duration of individual eruptive events within flood basalt provinces.

Our statistical model currently assumes that the Earth is vulnerable for the entire duration of magmatism of flood basalt provinces. Depending on how the environment responds to volcanic stresses, this could be an erroneous assumption. If, for example, loading of the atmosphere with CO_2 and global warming is the principle stress factor, the duration of the effects of the volcanism will exceed the total eruptive duration. On the other hand, if ecosystems are only significantly stressed during the actual periods of eruption (plus a few years afterwards while sulphate aerosols are still present in the stratosphere), t_{volc} will be substantially lower, and the probability of coincidence with impact be much smaller. There is a probability trade-off: smaller (more likely) impacts are required to tip the balance in favour of extinction if they coincide with a limited-duration period of acute stress; larger (less likely) impacts will be needed to cause extinctions during more extended periods of lower stress.

This reasoning can be extended to a larger scale. It is logical to suppose that, given two flood basalts provinces of equal dimensions but with different total durations, the environment will undergo more acute stress for the flood basalt province that is erupted more rapidly, because the eruptions must either be larger, or more frequent. The probability of a coincidence between volcanism and impact of a particular size, however, decreases, because t_{volc} is lower. If the hypothesis is correct that the largest mass extinctions are caused by a combination of volcanism and impact, we can predict the threshold crater size, which, when combined with a flood basalt episode, would cause a major mass extinction.

Assuming 12 continental flood basalts, the statistical model can be used to reproduce exactly three coincidences over 300 million years to match the 3 big extinctions: probability maxima are obtained for combinations of flood basalts having effects lasting

2 m.y. with impact craters exceeding 93 km, for 1-m.y. flood basalts and craters larger than 65 km, and for 0.5-m.y. flood basalts and craters larger than 46 km. (In each case, the probability of at least three coincidences remains approximately constant, at ~56%.) If the model is required to reproduce exactly four coincidences over 300 million years, probability maxima are obtained for crater sizes exceeding 80, 56 and 40 km, for flood basalts having effects of 2, 1 and 0.5 m.y., respectively. If similar calculations were performed including oceanic plateau volcanism as well as continental flood basalt provinces, the crater size threshold would increase in each case, but this is difficult to quantify because of the poor constraints on the number of oceanic large igneous provinces over the last 300 million years.

5.2. Impacts in the geological record

The discovery of impact-derived anomalies in the sedimentary record is not in itself evidence for large impacts: even impacts that create craters as small as 20 km have the potential to cause atmospheric blow-out and global dispersion of products (Grieve, 1997). Over 300 m.y., three or more coincidences between flood basalts and impactors causing ≥20-km diameter craters are almost inevitable (Figs. 3 and 4). Even with a crater size of $D \geq 100$ km, the probability of at least three coincidences is as high as 46%. Unfortunately, until impact craters (if they have been preserved) are discovered at the P–Tr and Tr–J boundaries, estimates of the size of any impacts will be poorly constrained. Alternatively, if we are to try to constrain impactor dimensions by mass balance constraints from analysed samples, we need an increased sample database so that the distribution of the impact marker is known, both globally, and in terms of vertical distribution within an impact bed. In addition, better constraints are required on the mass fraction of impactor material that eventually gets incorporated into impact deposits.

Impact cratering should be a common geological process, yet searches for terrestrial evidence of impact have yielded remarkably little. This implies either that the Earth has been unexpectedly lucky, that estimates of impact rates are wildly inaccurate, or that impact markers are difficult to find or are not always preserved. It is likely that evidence of some impacts has yet to be found: the searches are time-consuming and most have concentrated on bio-event horizons rather than palaeontologically unremarkable portions of the stratigraphic record (e.g., Orth et al., 1990), or focused only on a specific impact marker (e.g., Ir: Kyte and Wasson, 1986). Additionally, plate tectonic processes renew oceanic crust on a timescale of ~100 m.y., as well as destroying evidence of impact in tectonically active regions.

If impacts really are as common as the cratering statistics suggest, proposals that impacts are the primary cause of significant global mass extinctions are flawed: there could have been as many as 18 Chicxulub-sized impacts and 60 $D \geq 100$ km impacts during the Phanerozoic. This does not rule out impacts as being a contributory factor in some mass extinctions, but it does suggest that the outcome is strongly dependent upon the condition of the system at the time of impact, i.e., whether the biosphere was already in a stressed state due to the effects of flood basalts, or other terrestrial processes such as sea level change or climate change.

6. Conclusions

Flood basalts, and possibly bolide impacts, appear to be temporally associated with the three largest mass extinction events of the last 300 Ma. There is a surplus of volcanic and impact events compared to the number of observed extinctions, and therefore neither flood basalts, in isolation, nor impactors, in isolation, are likely to have caused these three extinctions. It is, however, feasible that either volcanism or impact could have acted as the sole cause of other, lesser, extinctions.

There is a realistic probability that large ($D \geq 100$ km) impactors coincidentally hit the Earth at the same time as major flood basalt magmatism at the P–Tr, Tr–J and K–T boundaries. If significant impacts at the P–Tr and Tr–J boundaries are verified, it implies that the juxtaposition of effects from volcanism and a bolide impact may be required to cause the largest mass extinctions. Depending on the relative timing of the two events, the mechanism for causing extinctions could be an ecosystem's inability to cope with the effects of an impact if already under stress from prolonged volcanic activity; alternatively, repeated volcanic eruptions following an impact could impede ecosystem recovery.

Even if future work does substantiate the reports of impacts at the P–Tr and Tr–J boundaries, the inference that the contemporaneous flood basalt provinces were somehow initiated by meteorite impact is unnecessary. Random chance alone can account for a number of coincidences between flood basalts and smaller impacts, and no causal link is required. Re-evaluation of a causal link between bolide impact and flood basalt magmatism will only be required if future research proves the existence of sizeable impacts (e.g., $D \geq 200$ km) that are contemporaneous with and spatially associated with flood basalt provinces, such that the probability of random coincidences is unrealistic.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.lithos.2004.09.016.

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