

Bicentennial Review

The geochronology of large igneous provinces, terrestrial impact craters, and their relationship to mass extinctions on Earth

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Abstract: The relationship between sudden catastrophic events and sudden mass extinctions on Earth has attracted a great deal of research effort, including measurements of the absolute and relative ages of these events. The result has been a rapid improvement in the precision and accuracy of radiometric dates for large igneous provinces (LIPs), for which there is now a consensus on the peak eruption times over the last 250 Ma. In parallel there has been a more gradual improvement in the radiometric dates for craters formed by hypervelocity impacts (HVIs) of asteroids and comets with Earth. The absolute ages of the largest craters are known to within a few million years but the ages of many smaller craters are poorly constrained. In addition, whereas relatively few LIPs have formed in the last 250 Ma, at least one HVI crater larger than 20 km diameter has formed on Earth every million years (only 25 such craters have been discovered), so coincidence between the ages of HVI crater formation and ages of mass extinctions is related as much to crater preservation as to coincidence of the events. The difference in quality of geochronology between HVIs and LIPs is the result of differing availability of samples: LIPs cover large areas and present an array of basalt samples suitable for dating, whereas HVI craters are often poorly preserved and present few datable samples. The radiometric data for preserved HVIs and LIPs are now sufficiently precise and accurate for us to be confident that there is no one-to-one correlation between either LIPs or HVIs and global mass extinctions of life on Earth. However, there is a close association between a significant number of LIPs and sudden environmental change, and a very close association between at least one massive HVI crater formation and a mass extinction. Further, there is no apparent correlation between HVIs and LIPs and thus no reason to suggest a causative relationship. Finally, the radiometric dating of HVI craters indicates several clusters in the geological record, but the correlation with sudden environmental change is no better than for large craters.

The subject of mass extinctions of life on Earth is too broad to cover in one review: it stretches from studies of the pace and potential mechanisms causing individual extinction events (Hallam & Wignall 1997) to statistical exploration of cyclicity in extinction rates with periods ranging from 25 to 62 Ma (Raup & Sepkoski 1982; Rohde & Muller 2005; Napier 2006). The intention here is to review the relationship between two types of catastrophic geological event and proposed mass extinction events as tested by geochronology, rather than to try to cover the many other debates on validity or mechanisms, in the hope that this will help to constrain the debate.

Both large igneous provinces (LIPs), and hypervelocity impacts (HVIs) of asteroids or comets with Earth have been hypothetically linked to the five major periods of mass extinction on Earth: the end Ordovician, mid-Devonian (Frasnian–Famennian), end Permian, end Triassic and end Cretaceous (see Hallam & Wignall 1997). Despite a continued debate on the causal relationships and pace of extinction during such events, and indeed the fact that mass extinction may have multiple causes (Macleod 2005), the drama of a sudden single catastrophe is an enticingly simple solution, and one that evokes an equally simple causal mechanism. In the best known mass extinction, at the end of the Cretaceous period, both a large LIP and a large HVI have been advocated as causal killing mechanisms (e.g. Alvarez *et al.* 1980; Courtillot *et al.* 1988). Other mass extinctions have been

explained as sudden catastrophes mainly by analogy with the KT event (e.g. Courtillot 1999; Becker *et al.* 2001; Wignall 2001; Basu *et al.* 2003). However, causality is extremely difficult to demonstrate and there are continuing debates on the structure and pace of many of the known mass extinction events.

A causal relationship between LIP eruptions and mass extinctions (e.g. Courtillot *et al.* 2000) has been ascribed to the release of SO₂ (e.g. Self *et al.* 2006), and sometimes CO₂ (e.g. Courtillot 1999), although the latter may have little effect because even the largest individual eruptions would not make a significant difference to the atmospheric CO₂ concentration (Self *et al.* 2006). Carbon isotope excursions (associated with the breakdown of marine and terrestrial ecosystems), thought to be related to methane clathrate release (Hesselbo *et al.* 2000), have also been associated with LIP eruptions.

The intense study of these problems has resulted in improvements in isotopic dating techniques, and the peak flow periods of LIPs have now been constrained using high-precision Ar–Ar dating, which has shown that most of them exhibit sudden high-flux events lasting less than 1 Ma, and sometimes more than one event (e.g. North Atlantic province, Courtillot & Renne 2003), but even this pace of eruptions may hide more rapid eruption rates that cause globally important environmental damage (Self *et al.* 2006).

Advocates of asteroid or comet impact have related global

mass extinction to SO₂ release, acid rain, wildfires, and high global dust levels, which give rise to reduced light and temperatures (Wolbach *et al.* 1988; Gilmour & Anders 1989; Toon *et al.* 1997; Kyte 1998; Gupta *et al.* 2001; Pope 2002; Keller 2003; Maruoka & Koeberl 2003). However, computer modelling of the consequences of HVI explosions (Kring *et al.* 1996; Melosh 1996; Kring 1997; Abramov & Kring 2004, 2005; Collins *et al.* 2005) show that only the largest impacts, producing craters in excess of 100 km diameter, have such global consequences. Smaller craters are likely to be associated with effects stretching only a few hundred kilometres from the impact site.

Finding the precise ages of HVI events is more challenging than dating LIP events. Dust and gases introduced into the stratosphere by large HVIs, such as the KT impact on the Yucatan peninsula of Mexico, have the potential to leave a permanent record in sediments (e.g. Smit 1999; Walkden *et al.* 2002; Kring *et al.* 2006; Morgan *et al.* 2006) and thus allow relative dating and correlation with the consequent extinctions of life. Unfortunately, HVI craters have proved much more difficult to date, both in absolute terms because of the challenging samples and in relative terms because of their superficial nature, making the validity of correlations sometimes questionable.

So how can geochronology move the debate on sudden mass extinctions forward? One of the main lines of evidence for a relationship between extreme events (LIP and HVI) and mass extinction at the end of the Cretaceous period has been the apparently simultaneous mass extinction, LIP eruption (Deccan Traps in India) and HVI (Chicxulub crater in Mexico). A general relationship between such events can be investigated by considering how often a synchronous HVI or LIP can be demonstrated at stratigraphic boundaries associated with extinction in the geological record. This can be achieved using both relative and absolute dates, but it is important to understand the difference between absolute and relative dating in this context. For example, synchronicity of catastrophic events and mass extinction has been demonstrated in relative terms, particularly between marine extinctions and globally distributed shock mineral grains and heightened Ir concentrations at the KT boundary (Alvarez *et al.* 1980; Smit 1999; Keller *et al.* 2004a, b; Morgan *et al.* 2006). This synchronicity is clearly demonstrated at time scales of a few thousand years by comparison of the Ir anomaly associated with the impact and sediment accumulation rates measured by extraterrestrial dust input (see Mukhopadhyay *et al.* 2001b). However, in absolute dating terms, the HVI and LIP events are constrained by Ar–Ar ages of the Deccan Traps and Ar–Ar dates of impact-produced tektites from Haiti. Ar–Ar dating shows that the Deccan LIP started to erupt around 68 Ma ago and peaked close to 65.5 Ma ago, subsiding rapidly but continuing until around 62 Ma (Basu *et al.* 1993; Hofmann *et al.* 2000; Widdowson *et al.* 2000). KT tektites from Haiti yield Ar–Ar ages for the HVI recorded by the crater at Chicxulub of 65.6 ± 0.1 Ma (recalculated to calibrated international mineral standards; Renne *et al.* 1998; Izett *et al.* 1991; Knight *et al.* 2003).

The absolute ages of the peak of Deccan eruptions and the Chicxulub tektites have been constrained by Ar–Ar dating and lie within 0.1 Ma, but they only constrain the absolute age of the events to better than around ± 0.5 Ma because both are constrained by the precision to which the potassium decay constant is known ($\pm 1\%$; see discussion by Renne *et al.* 1998). The precision of the decay constant is less important if all ages are reported relative to the same decay constant and standards, but not relative to other decay schemes and relative ages based on stratigraphic correlations, which commonly rely on U–Pb dates.

This review reports all Ar–Ar ages relative to the conventional decay constant (Steiger & Jäger 1977) and standards (Renne *et al.* 1998). The most important consequence of this is that the age of the KT boundary is 65.6 Ma (Knight *et al.* 2003) rather than 65 Ma as commonly reported. It should be noted, however, that the most recent time scale shows the KT boundary at 65.5 ± 0.3 Ma (Gradstein *et al.* 2005). However, the rapid time scale of the extinction event (<10 ka, Mukhopadhyay *et al.* 2001b) and precision of Ar–Ar dating technique precludes its use to determine the relative progression of the end-Cretaceous extinction.

Despite the problems of using radiometric dating to monitor the pace of extinction, dating has played a central role in the debate on causal relationships between LIPs, HVIs and mass extinctions. A case has been made for repeated correlation of mass extinctions with both LIPs (Wignall 2001; Courtillot & Renne 2003), and HVIs (Rampino & Stothers 1986; Stothers 1989, 2006; Napier 1998, 2006) based on their ages determined by radiometric dating. In fact, radiometric dating offers a practical and precise method for checking repeated coincidence, and thus potentially discriminating between hypotheses advocating LIPs and HVIs as causal mechanisms in mass extinction events. If they are indeed causal, such events should coincide repeatedly with sudden climate change, and/or mass extinctions.

Radiometric dating of LIPs and large terrestrial impacts

Although there are several hypotheses that link LIPs, HVIs or both with mass extinctions, the resultant structures present very different challenges to researchers trying to obtain a precise age. K–Ar and Ar–Ar dating techniques have most commonly been used for both LIPs and HVI craters, although the more precise U–Pb technique also plays a role (e.g. Hamilton *et al.* 1998; Riley & Knight 2001; Kamo *et al.* 2003). However, whereas the peak flow periods of all major LIPs have now been dated precisely using the Ar–Ar dating technique, only the largest craters have been dated and many medium-sized impact craters have been dated using only stratigraphic relationships. Alvarez (2003) pointed to the main cause of this disparity. Whereas LIPs cover vast areas and present many cubic kilometres that can be sampled and dated, terrestrial impacts are commonly less than 100 km in diameter and associated with very small amounts of melted rock from which samples suitable for isotopic dating might be obtained. Further, the small amounts of datable material in HVI impacts are clast-rich glasses subject to the same problems of alteration and excess argon as seen in LIP basalt glass, but with the additional problem of multi-clast contamination.

Use of radiometric dating to determine the ages of LIPs

Prior to the widespread application of Ar–Ar dating to LIPs, the literature on K–Ar ages seemed to indicate prolonged eruption times for these enormous provinces. For example, K–Ar dates on the Paraná basalts in Brazil indicated eruption ages ranging from 165 Ma to 80 Ma, peaking around 130 Ma (Fig. 1). Although it was known that excess argon and argon loss might affect K–Ar values, and the full range was likely to contain some invalid ages, it was thought that such eruptions might last tens of millions of years. It was only with the use of Ar–Ar dating that the true peak eruption period from around 130 to 133 Ma was determined (Hawkesworth *et al.* 1992; Renne *et al.* 1992, 1996;

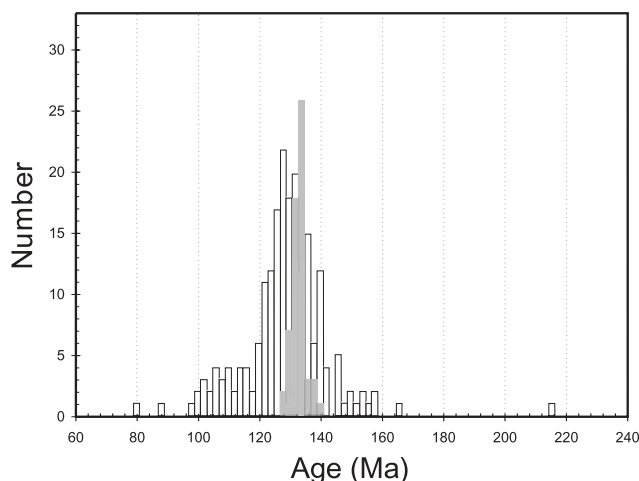


Fig. 1. A histogram of 200 K–Ar and 50 Ar–Ar ages for the Paraná LIP of Argentina.

Turner *et al.* 1994; Stewart *et al.* 1996), revealing the true peak of eruption lasting less than 3 Ma (Fig. 1). The main problem with the K–Ar ages is that the analysis requires relatively large samples (*c.* 0.1–1 g) and it has proved difficult to completely remove the effects of contamination and alteration in such samples, particularly in low-potassium rocks such as basalts. K–Ar dates of basalts tend to be analyses of whole-rock samples, making alteration of volcanic glass a particular challenge. Moreover, in many tholeiitic basalts (from which LIPs are constructed) the main phenocryst phase is plagioclase with very low potassium (commonly 0.1%), compared with 0.5–1.5% in the whole rock. This is because the main potassium-bearing phase is commonly the interstitial glass, but this is also the most likely phase to be altered, and is most likely to contain excess argon. Alteration of glass is the main cause of the large population of apparently young ages in the Paraná K–Ar age distribution (Fig. 1). Excess argon is a less prevalent problem in the Paraná K–Ar age distribution, yet it is clearly a significant problem, particularly in glass (Kelley 2002), and contributed to the smaller population of old ages in the Paraná array (Fig. 1). The development of high-precision techniques for Ar–Ar dating achieved reproducible and precise ages by taking advantage of the ability to date small acid-cleaned whole-rock samples and plagioclase mineral separates (*c.* 10 mg) (e.g. Renne & Basu 1991; Renne *et al.* 1992). The Ar–Ar technique caused a rapid innovation in our understanding of LIP eruptions, showing that they had extremely high eruption rates (see review by Courtillot & Renne 2003). Improved Ar–Ar dating has shown that LIP eruptions may have short periods of extremely high magma flux, at rates that might induce environmental breakdown (Sephton *et al.* 1999; Ravizza & Peucker-Ehrenbrink 2003; Watson *et al.* 2005; Self *et al.* 2006).

The measurement of precise absolute ages of LIPs is now a mature area of science based on extensive studies of well-exposed continental flood basalts such as the Deccan, Paraná–Etendeka and Karoo–Ferrar Provinces. However, extrapolation of single short eruption model to all provinces may be premature, as some clearly have double eruptions (North Atlantic Igneous Province), and some are poorly constrained because of lack of exposure (for instance, large areas of the Siberian Traps are buried and are accessible only in drill cores, Reichow *et al.* 2005), or, like Ontong–Java, are submerged beneath the ocean.

Recent reviews (Wignall 2001; Courtillot & Renne 2003) used very similar databases of LIP ages to discuss the relationship between LIP eruptions and mass extinctions. Although the two reviews differed in their interpretation, both concluded that there is a significant correlation between the larger LIPs and mass extinctions.

Use of radiometric dating to determine the ages of HVIs

Whereas the peak flow times of almost all known Phanerozoic LIPs are known to within 1 Ma, dating of terrestrial impacts is far less complete. The ages of the largest terrestrial craters containing large quantities of melt, such as Manicouagan in Canada (214 ± 1 Ma, Hodych & Dunning 1992), or those associated with global dust horizons, such as Chicxulub in Mexico (Smit 1999; Morgan *et al.* 2006), are well constrained. However, smaller craters, for example, the Ries crater in Germany (24 km diameter), produced thick ejecta layers, but Ar–Ar dating performed on the unmelted ejecta rocks yields the age of the surrounding rocks, not the impact age, and so is unsuitable for use in measuring the HVI age. Only melted rocks that have undergone complete resetting of the K–Ar or Ar–Ar system can yield the true HVI age (e.g. Jessberger *et al.* 1978). Unfortunately, many of the hypotheses concerning clustering and periodicity of meteorite impacts on Earth have been established on poorly constrained crater ages, and are thus difficult to evaluate and are potentially flawed. Only attempts to understand the integrated terrestrial impact history are free from this constraint, as precise ages are not crucial (e.g. Grieve 1991; Grieve & Pesonen 1996; Bland *et al.* 1998; Shoemaker 1998; Hughes 2000).

Very large HVI craters, such as the 300 km diameter Vredefort crater (2023 ± 4 Ma, Kamo *et al.* 1996; Moser 1997) in South Africa and the 250 km diameter deformed Sudbury impact structure in Canada (1850 ± 3 Ma, Krogh *et al.* 1982), formed large melt pools in their cores, which cooled and crystallized to form igneous rock of syenitic composition. The zircons that crystallized from these melts formed rapidly following impact, and yield precise dates on these very ancient craters. However, craters smaller than 100 km diameter exhibit only thin melt layers that may represent welded suevite (e.g. Boltysh crater, Gurov & Gurova 1985; Grieve *et al.* 1987; Kelley & Gurov 2002). Melts of various types have proved to be the only samples suitable for precise radiometric age determinations. Tektites, melt droplets that have fallen back to Earth, have yielded precise radiometric ages, even when they are not clearly associated with a crater (e.g. Koeberl *et al.* 1997). Indirect methods of dating impact have also been successful in dating HVIs; for example, dating of authigenic K-feldspar that rapidly cemented HVI spherules (Walkden *et al.* 2002) and heated basement K-feldspar (Zeitler 1996).

The floors and walls of HVI craters are subject to post-impact tectonic reorganization, which lead to the formation of friction melts, or pseudotachylites (Spray 1988, 1992; Reimold 1991), and it has been shown that such melts can yield the age of the HVI (e.g. Spray *et al.* 1995). The most commonly dated samples in HVI craters are thus either impact melts or pseudotachylites. In addition, it is important to distinguish melts caused by shock from those caused by friction, although both types of melt have the potential to yield the age of HVI (Spray *et al.* 1995). Whether shock or friction melts, such melts commonly contain very significant host rock contamination and the contaminating clasts and mineral grain fragments are present on all scales from

metre-sized blocks seen at a locality scale to dust-sized particles within individual samples.

Radiometric ages on pseudotachylites and melt rocks are also subject to the same problems of alteration, argon loss and excess argon as observed in LIP basalts because the main potassium-bearing phases are either glasses or fine-grained igneous rocks, which lose argon via diffusive loss or alteration during post-impact hydrothermal fluid flow, later burial and alteration of the crater (Thompson *et al.* 1998), or long-term diffusive loss during storage at shallow depths (Spray *et al.* 1995). Despite such problems, many of the precise and reproducible ages for Phanerozoic era craters have been measured using the Ar–Ar dating technique. The key to this reproducibility has been repeated analysis to test reproducibility. For example, the 100 km diameter Popagai crater in Russia was dated at 35.5 ± 0.1 Ma (Bottomley *et al.* 1997) by repeated analysis of several size fractions and mineral separates. Analyses of other craters illustrate the importance of dating a suite of samples to understand the behaviour of argon in glasses and suevites. For example, K–Ar ages of melts from the Boltys HVI crater in Ukraine yielded ages ranging from 55 to 90 Ma (Kelley & Gurov 2002), but detailed Ar–Ar analyses showed that the melts retained some portion of pre-impact radiogenic argon, dissolved in the melt rather than retained in the clasts. Ar–Ar analyses of carefully screened samples with the greatest proportion of igneous textured crystals and little glass yielded reproducible ages and a mean of 65.14 ± 0.64 Ma, within error of the age of the larger Chicxulub HVI crater (Kelley & Gurov 2002). Notably, where pseudotachylites have formed in terrestrial fault movement events, laser extraction and step-heating Ar–Ar techniques have been used to circumvent the problems in some cases and reveal fault movement ages (Kelley *et al.* 1994; Magloughlin *et al.* 2001; Sherlock & Hetzel 2001; Muller *et al.* 2002).

A consequence of the challenge of obtaining precise and reproducible radiometric ages for intermediate and small HVI craters (3–50 km diameter) is that the ages of many such craters are constrained only on the basis of stratigraphy. In other words, the impact is known to be younger than the target rock from which the crater formed, but older than the crater-filling sediments. Sometimes this technique can yield tight age constraints (Smelror *et al.* 2001; Dypvik *et al.* 2004), but other HVI craters have only a maximum age constraint from the target rock. Crater counting and overlap, which provides strong constraints for crater ages on other bodies such as the Moon and Mars (Hartmann & Neukum 2001; Neukum *et al.* 2001), does not work on the Earth with its constantly reworked surface, and only two craters on Earth can be dated relative to one another. The 2.7 km diameter Rotmistrovka crater in Ukraine must predate the Boltys crater also in Ukraine, as the former contains an ejecta layer from the latter. Radiometric dating has yielded an age of 65.17 ± 0.64 Ma for Boltys and stratigraphic constraints yield an age of 120 ± 10 Ma for Rotmistrovka, confirming the relationship.

The consequence of complexities in the determination of HVI ages is that individual crater ages, particularly those dated by the K–Ar technique, may be inaccurate, even though the experimental errors indicate a precise age determination. Many HVI crater ages are based on K–Ar ages and any hypotheses based on the older crater database ages are flawed.

In summary, the geochronology of meteorite impacts is improving, but it is less well constrained than the geochronology of LIPs. However, the record is now sufficiently improved to consider potential HVI clusters in the record and HVI periodicity, and to compare HVI ages with LIP ages and the newly

recalibrated stratigraphic ages for boundaries associated with known mass extinctions (Gradstein *et al.* 2005).

LIP eruption ages and their relationship with stratigraphic boundaries and periods of mass extinction

There are indications of at least two periods of intense LIP activity (superplumes), during the Permian–Carboniferous and the Cretaceous periods although the total extent, and thus importance, of older provinces is very difficult to establish. The continuous subduction of ocean crust means that as much as four times the present area of ocean floors has been lost in the last 400 Ma and it is likely that some oceanic LIPs may never be detected. By considering only the last 260 Ma, we can capture most of the recent oceanic LIPs and almost certainly all the continental LIPs. Courtillot & Renne (2003) reviewed the geochronology of LIPs and producing a database of the peak eruption times (Table 1); those workers concluding that they represent major geodynamic events with magma eruption rates far exceeding the present output from hotspots, and even exceeded the mid-ocean ridge output for short times. Courtillot & Renne (2003) proposed a strong correlation between LIP ages and the ages of mass extinctions or periods of global oceanic anoxia (Fig. 2), and in particular the four largest mass extinctions in the last 260 Ma (end Guadalupian, 258 Ma; end Permian, 251 Ma; end Triassic, 200 Ma; end Cretaceous, 65 Ma). Courtillot & Renne (2003) showed that these extinction events were particularly closely correlated with the peak of four LIP eruptions: Emeishan Traps (Dobretsov 2005), Siberian Traps (Renne & Basu 1991), Central Atlantic Magmatic Province (Marzoli *et al.* 1999; Hames *et al.* 2000) and Deccan Traps (Courtillot *et al.* 1988; Duncan & Pyle 1988; Hofmann *et al.* 2000). Further, Courtillot & Renne (2003) held that close correlations could be found between the ages of all known LIPs and times of sudden environmental change (mass extinction) events, and interpreted the data as indicating a causal link between LIP eruptions and mass extinctions through catastrophic climatic perturbations. They also concluded that the time sequence of LIPs shows no pattern of eruption with time, an observation confirmed more recently using wavelet analysis (Prokoph *et al.* 2004). In addition, Courtillot & Renne (2003) pointed out that, unlike HVI craters, the size range of LIPs does not follow a power-law distribution; in fact, their size range is only slightly greater than one order of magnitude.

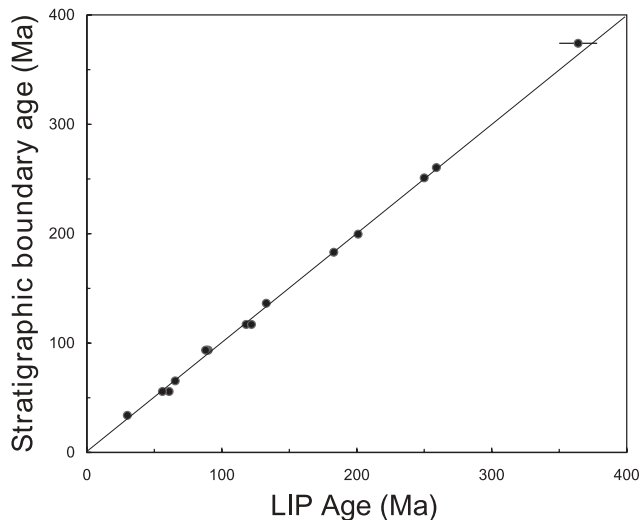
In another review of the relationship between LIPs and mass extinctions, Wignall (2001) concluded that there is a strong relationship between some LIPs and mass extinctions, but that correlations of all LIPs with extinction events are unduly optimistic. In contrast to Courtillot & Renne (2003), Wignall (2001) believed that the onset of the LIP eruptions often post-dated the mass extinction and that only the eruption of the Deccan Traps coincided precisely with a mass extinction. Wignall (2001) showed that the data indicated no correlation between the extinction intensity and either volume or rapidity of the LIP eruptions, although, as Courtillot & Renne (2003) pointed out, there is less than an order of magnitude difference between the largest and smallest LIP. In particular, Wignall (2001) pointed to the lack of any correlation between a global environmental event and the eruption of the Paraná–Etendeka flood basalt province, which accompanied the opening of the South Atlantic.

In summary, although the LIP age databases used by Courtillot & Renne (2003) and Wignall (2001) are very similar (see Table

Table 1. Peak eruption ages for LIP eruptions, and associated stratigraphic boundaries associated with sudden environmental change

Large igneous province	Mean age (Ma)	Stratigraphic boundary age (Ma)	Age of stratigraphic boundary (Ma)
Viluy Traps	364 ± 14	End Frasnian	374 ± 2.6
Emeishan Traps	259 ± 3	End Guadalupian	260.4 ± 0.7
Siberian Traps	250 ± 1	End Permian	251 ± 0.4
Central Atlantic Magmatic Province	201 ± 1	End Triassic	199.6 ± 0.6
Karoo–Ferrar Dronning Maud Land	183 ± 2	End Pliensbachian	183 ± 1.5
Paraná–Etendeka	133 ± 1	End Valanginian	136.4 ± 2
Rajmahal–Kerguelen	118 ± 1	End Early Aptian	117 ± 2.5
Ontong–Java 1	122 ± 1	End Early Aptian	117 ± 2.5
Ontong–Java 2	90 ± 1	End Cenomanian	93.5 ± 0.8
Caribbean plateau	89 ± 1	End Cenomanian	93.5 ± 0.8
Madagascar Traps	88 ± 1	End Cenomanian	93.5 ± 0.8
Deccan Traps	65.5 ± 0.5	End Cretaceous	65.5 ± 0.3
North Atlantic Igneous Province 1	61 ± 2	End Early Palaeocene	55.8 ± 0.2
North Atlantic Igneous Province 2	56 ± 1	End Palaeocene	55.8 ± 0.2
Ethiopian and Yemen Traps	30 ± 1	Oi2 event	30 ± 2.5
Columbia River	16 ± 1	End Early Miocene	15.97 ± 0.1

Mean ages are derived mainly from Courtillot & Renne (2003), and stratigraphic boundaries are from Gradstein *et al.* (2005).

**Fig. 2.** Peak eruption ages for LIP v. ages for stratigraphic boundary associated with sudden environmental change, oceanic anoxia event and/or mass extinction.

1), they used different criteria to judge coincidence and reached very different conclusions. Courtillot & Renne (2003) concluded that all LIPs are correlated with times of sudden environmental change; Wignall (2001), on the other hand, concluded that only five of around 11 correlated. Wignall also noted that the onset of volcanism generally post-dated the extinction events, and that the best correlations were with mid-Phanerozoic LIPs, whereas only one of the seven more recent LIPs (the Deccan Traps) showed close correlation with sudden environmental change and mass extinction. Wignall (2001) also noted that six of 11 provinces were associated with periods of global warming and marine anoxia or dysoxia but that the associated carbon isotope excursions could not be explained by volcanic CO₂ release alone.

The publication of a revised geological time scale for the Phanerozoic eon allows us to quantify the LIP or HVI v. stratigraphic boundary relationship (Gradstein *et al.* 2005). There

are several options for considering this relationship and the most commonly used is a plot of LIP age v. mass extinction age (e.g. Courtillot 1999; Courtillot & Renne 2003), shown in Figure 2. The plot tends to produce a line with a slope of one and makes deviations of less than 5 Ma difficult to see, although such differences are crucial to understanding the relationship. In fact, there is a more fundamental problem with the plot, as each LIP is likely to be assigned only to the closest mass extinction event, and the extinctions are separated by on average 25 Ma. Large areas of the plot are therefore inaccessible. An alternative plot (Fig. 3), illustrates the difference in age between LIP peak eruption age and stratigraphic boundary age (Gradstein *et al.* 2005), plotted against the peak LIP eruption age. In addition, since the new International Commission on Stratigraphy ages has estimated errors on absolute ages of stratigraphic boundaries, it is possible to propagate errors for the age difference and view the errors relative to the difference (Fig. 3). It should be noted that two data points are shown for the North Atlantic Igneous Province, which has well-described dual eruption peaks at 61 ± 2 and 56 ± 1 Ma. A second peak is also shown for the 122 ± 1 Ma Ontong–Java province, although the validity of the later 90 Ma peak has been questioned (Fitton *et al.* 2004). In addition, Courtillot & Renne (2003) assigned the two most recent LIPs, the Ethiopian–Yemen Traps (30 ± 1 Ma) and Columbia River flood basalts (16 ± 1 Ma), to sudden environmental change events, oxygen isotope excursion event (Oi2), which indicated cooling in the early Oligocene (one of six such events at a similar time, the largest of which was oxygen excursion event 1 (Oi1) at the Oligocene–Eocene boundary, 33.9 ± 0.1 Ma), and a poorly constrained late Miocene extinction. Wignall (2001) dismissed correlation of the Ethiopian–Yemen Traps with any extinction or climate event, as the major extinction occurred in the late Eocene, predating the Traps by around 4 Ma. Moreover, Ukstins *et al.* (2002) showed that large ignimbrite eruptions in the lower part of the flood basalt sequence in Yemen post-dated the Oi2 global cooling event. Wignall (2001) also dismissed any correlation of the Columbia River flood basalts with an extinction event, as the synchronous extinctions were in deep benthic Foraminifera and were attributed by others to long-term cooling of the deep ocean waters, and mammalian extinctions in North

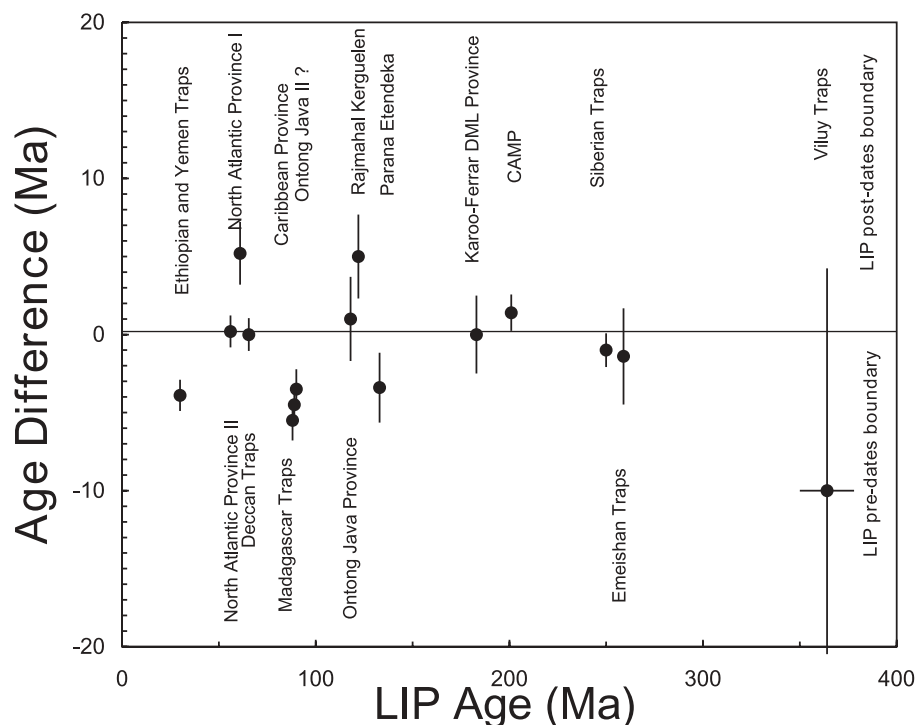


Fig. 3. Age difference between LIP and associated sudden environmental change v. age of a stratigraphic boundary associated with sudden environmental change. CAMP, Central Atlantic Magmatic Province.

America occurred several million years after the eruptions. Columbia River flood basalts are also by far the smallest LIP (less than one-tenth the size of the Deccan Traps) and will not be used in later correlations with global environmental change events.

The first observation concerning Figure 3 is that six of 15 major LIP eruptions over the last 300 Ma fall within error of a stratigraphic boundary associated with major environmental disturbance and the mean difference of all points from the stratigraphic boundary is 2.5 Ma. It should be noted that the use of absolute ages for stratigraphic boundaries in this plot is a simplification, as most of the important stratigraphic boundaries are not dated directly but have their ages derived using a spline fit based on radiometrically dated events such as tuff horizons (Gradstein *et al.* 2005). The error associated with the spline fit is the main source of error in Figure 3.

With the LIP ages normalized to boundaries associated with sudden environmental change, it becomes clear that although there is a clear association between LIPs and environmental change, the peak eruption ages of several LIPs did not coincide with times of sudden environmental change or mass extinction events. As Wignall (2001) noted, several LIP eruptions appear to post-date the environmental change. In particular, the peak eruption of the Parana–Etendeka province post-dates the end-Valanginian boundary, a minor oceanic anoxic event (OAE) during the Cretaceous period, even though the boundary was moved to a younger age in the recent International Commission on Stratigraphy reappraisal (Gradstein *et al.* 2005). The Parana LIP peak eruption age is well constrained and unlikely to change significantly, and the only significant extinction event close to this age is the end-Tithonian event (145.5 ± 4.0 Ma), which occurred over 10 Ma earlier. The other notable non-coincidence is the combined Caribbean–Madagascar eruptions, which now appear to post-date the Cenomanian–Turonian boundary (known at the Bonarelli event, one of two global OAE during the

Cretaceous) by 3–5 Ma, throwing the earlier interpretation of their coincidence (Kerr 1998) into doubt. The eruption of the Rajmahal Traps and Kerguelen plateau predate the end-early Aptian boundary (the Selli OAE event around 120 Ma) by as much as 5 Ma, and there seems little likelihood that the absolute dates are inaccurate by as much as 5 Ma. Finally, the earlier of two North Atlantic LIP eruption peaks predates the end-Palaeocene boundary by around 5 Ma (the end-Palaeocene event is not associated with major extinction losses but is associated with sudden warming, an event known as the Palaeocene–Eocene Thermal Maximum or PETM) but the later eruption phase appears coincident with the end of the Palaeocene. The rocks of northern Scotland and Greenland contain strong evidence of a sudden warming event within the earlier phase of eruptions, around 58–60 Ma (Norris & Rohl 1999; Jolley *et al.* 2002), but not in the later phase (*c.* 55 Ma), and further work continues to unravel this dilemma. Further, there is no evidence of an extraterrestrial input (Schmitz *et al.* 2004) at the PETM.

Finally, the data shown in Figure 3 represent a simplification of the true situation, as it shows all known LIPs but does not show all known sudden environmental change events. For example, the only major OAE during the Jurassic period, the Toarcian event, coincides very closely with the only major LIP (Karoo–Ferrar). However, there are several OAEs during the Cretaceous period; one (the Selli event) during the early Aptian appears to correlate with eruptions in the Pacific Ocean, whereas the later major OAE, the Bonarelli event, which occurred at the Cenomanian–Turonian boundary, is placed at 93.5 ± 0.8 Ma by the time scale, clearly predating three major LIP eruptions that occurred close to 90 Ma (Fig. 3).

In summary, Figure 3 shows the very close association between LIP eruptions and times of sudden climate change. Six of 15 LIP eruptions correlate with sudden environmental change within the errors of the methods used, and almost all the remaining LIP events erupted during the Cretaceous period.

HVI crater ages and their relationship with stratigraphic boundaries and periods of mass extinction

There are currently over 174 confirmed impact craters on Earth, ranging in diameter from as little as a few tens of metres to 300 km. No attempt is made here to reproduce a table of HVI craters, as the numbers of confirmed craters increases on a monthly basis. The Planetary and Space Science Centre (PASSC) at the University of New Brunswick in Canada maintains the most up-to-date database available, on their website (<http://www.unb.ca/passc/ImpactDatabase/index.html>). The PASSC database includes crater size and age information, images and references, and will be used in this review.

Most HVI crater ages are determined on the basis of radiometric dating of melted target rock, and thus the larger craters tend to be the best constrained: the ages of 71% of craters >10 km diameter are known to within 10 Ma, and the figure is 83% for craters greater than 20 km diameter. In other cases, the crater ages are only partially constrained, either to a minimum (e.g. the age of Crawford crater in Australia is >35 Ma, constrained by the age of overlying sediments) or a maximum (e.g. Aorounga in Chad, which has an age of <345 Ma (the age of the target rocks)). Some craters are constrained by maximum and minimum ages but still the difference represents poor constraint, such as the 12 km diameter Wells Creek crater in the USA, which formed between around 300 and 100 Ma ago. Only the ages constrained by isotope geochronology are used in this review, apart from one, the Mjolnir crater, which is constrained using high-resolution stratigraphy (Smelrøer *et al.* 2001).

The main challenge to using the crater record in the same way as the LIPs is that the terrestrial crater record, like the fossil record, is very dependent upon preservation. Craters formed in the oceans are, for example, much less likely to have been discovered, and their preservation is limited by subduction of the ocean crust. However, the number of HVI craters on Earth can be estimated from several sources including the lunar cratering record (Stöffler *et al.* 2006), the record of large impacts on long-lived stable cratonic areas of the Earth (Grieve & Shoemaker 1994; Grieve & Pesonen 1996; Shoemaker & Shoemaker 1996; Shoemaker 1998; Hughes 2000), and the population of modern near-Earth objects (asteroids and comets with orbits that pass close to that of the Earth) (Stuart & Binzel 2004).

As modern measurements of near-Earth asteroids have led to the estimate that 1 km asteroids form holes around 20 km diameter when they impact on Earth, we will consider craters of that size. Calculations based upon the lunar impact record indicate that craters larger than 20 km diameter form at a rate of $5 \times 10^{-15} \text{ km}^{-2} \text{ a}^{-1}$ (Stöffler *et al.* 2006), equivalent to one crater every 0.4 Ma (assuming a surface area for the Earth of $510 \times 10^6 \text{ km}^2$ to two significant figures). This HVI rate is similar to estimates based upon cratonic areas of the Earth's crust, which range from 3×10^{-15} to $5 \times 10^{-15} \text{ km}^{-2} \text{ a}^{-1}$, equivalent to one crater every 0.4–0.7 Ma (Barlow 1990; Grieve & Shoemaker 1994; Grieve & Pesonen 1996; Shoemaker & Shoemaker 1996; Shoemaker 1998; Hughes 2000). Based on the assumption that objects larger than 1 km form craters larger than 20 km, the estimate based on the observed near-Earth object population (Stuart & Binzel 2004) is one crater every 0.6 Ma, equivalent to an HVI rate of $3.3 \times 10^{-15} \text{ km}^{-2} \text{ a}^{-1}$. Thus the various estimates indicate that craters larger than 20 km diameter form on Earth, on average, once every 0.4–0.7 Ma. Given that almost all known terrestrial craters are preserved on continental crust, a more useful parameter is that one crater larger than

20 km diameter forms on continental crust every 1–2 Ma. Assuming the HVI rate has been roughly constant (see discussion below on impact clusters), between 270 and 540 craters of >20 km diameter must have formed on Earth during the Phanerozoic eon. However, the record of confirmed craters (<http://www.unb.ca/passc/ImpactDatabase/>) contains only 34 Phanerozoic craters of >20 km diameter, which represents 6–13% of the complete record. Clearly, with around 90% of the crater record missing, inferences concerning correlations between HVIs and sudden climate change events are subject to very significant uncertainty. In fact, the probability that one HVI crater formed within 1 Ma of every stratigraphic boundary in the Phanerozoic is close to one, whereas the probability that the same crater has been preserved and found is around 0.1.

A result of preservation record of craters is the fact that much of the controversy over correlations between HVIs and sudden environmental change events has focused upon boundaries where there is no known crater. There are debates on potential involvement of HVIs at the Triassic–Jurassic (TJ) boundary based on an Ir anomaly in sediments (Olsen *et al.* 2002) and the Permian–Triassic (PT) boundary based on the presence of C_{60} and meteorite fragments in sediments of that age (Becker & Poreda 2001; Becker *et al.* 2001, 2004a, b; Basu *et al.* 2003). Although there is no strong evidence for shocked quartz fragments (the most commonly used indicator of a large impact with global consequences) at either the TJ or PT boundary, it has been argued that such evidence might not be present if the event were related to an oceanic HVI, which would not produce shocked quartz. Further, while the debates on these boundaries continue, it should be noted that the original discovery of the KT boundary event was based not upon the discovery of a crater but on the finding of a thin layer of sediment containing shocked quartz and anomalously high concentrations of Ir (Alvarez *et al.* 1980), and it was not until nearly 10 years later that a crater on the Yucatan peninsula in Mexico was identified as the source (Hildebrand *et al.* 1991; Sharpton *et al.* 1992). Even now the evidence for the KT boundary correlation continues to be debated, with some researchers claiming evidence for more than one impact ejecta layer proximal to Chicxulub (Keller 2001; Keller *et al.* 2004a, b; Stinnesbeck *et al.* 2004), whereas others have found only one layer (Smit *et al.* 1994, 2004; Smit 1999), and recent work on the global sections found only one layer (Morgan *et al.* 2006).

The aim of this review is to consider absolute ages of confirmed HVI craters. Although this is approach will not find all correlations, it will illuminate the level of coincidence and allow a direct comparison with LIPs. There are two possible approaches: (1) searching for correlations between sudden environmental change or mass extinctions and the ages of the largest known HVI craters; (2) searching for correlations between sudden environmental changes and clusters of HVI craters in the record.

Figure 4 illustrates the correlation between the largest craters (>40 km diameter) and boundaries associated with sudden environmental change. The plot appears to show a close association between HVIs and such boundaries. However, this plot is similar to the plot for LIPs (Fig. 2), and has the same shortcomings in that the data can occupy only a small area of the plot around the line with slope of one because each HVI is considered for correlation only with adjacent stratigraphic boundaries. Figure 5 illustrates the age difference between HVIs and stratigraphic boundaries plotted against HVI age and shows that the ages of four of the 12 largest craters overlap boundaries associated with sudden environmental change. It should be noted,

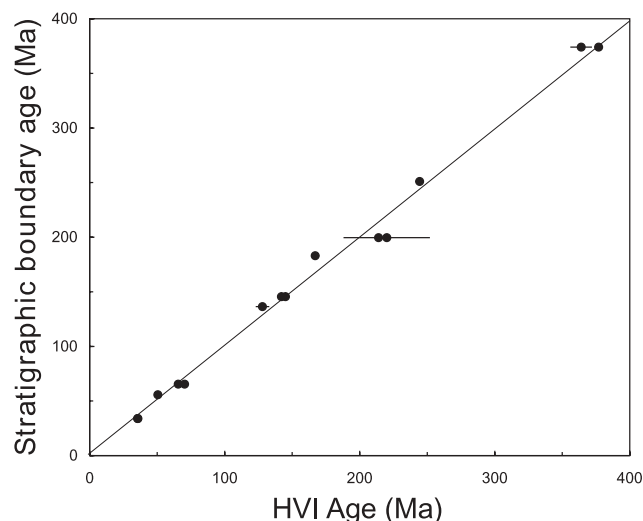


Fig. 4. Peak eruption ages for HVI craters v. ages for stratigraphic boundary associated with sudden environmental change, oceanic anoxia event and/or mass extinction.

however, that the main contribution to the error is the error on the age of the stratigraphic boundaries. The data appear more scattered than in the equivalent plot for LIPs (Fig. 3) and this is borne out by the mean deviation of 6.1 Ma for the data (the mean deviation for LIPs is 2.5 Ma). The mean deviation of large HVI crater ages is greater than the errors associated with both stratigraphical boundaries and large craters, and demonstrates that there is no match between the ages of the largest know HVI craters and times of sudden environmental change. Although

several studies have proposed HVI–mass extinction correlations (Rampino & Stothers 1986; Stothers 1989, 2006; Napier 1998, 2006; Glikson 2005) they rely upon smaller craters, known to occur at rates greater than one every 1 Ma, to achieve a fit between HVIs and sudden environmental change. It can be argued that the presence of several craters within error of each other indicates a cluster, but fits between small craters and sudden environmental change probably owe as much to crater preservation as to original HVI rates.

In detail, Figure 5 shows that the ages of confirmed craters of >40 km diameter overlap stratigraphical boundaries in only four places: the Chicxulub crater formed within error of the KT boundary at 65.5 Ma, the Morokweng and Mjøltnir craters formed within error of the end-Jurassic boundary at 145.5 Ma, and the Siljan crater formed within error of the Frasnian–Famennian boundary at 374.5 Ma. The coincidence of the Morokweng and Mjøltnir HVI craters with the end-Jurassic boundary is noteworthy. The two craters were not synchronous, as high-resolution stratigraphic evidence shows that the Mjøltnir HVI occurred after the end-Jurassic boundary (Smelror *et al.* 2001; Dypvik *et al.* 2004), but the conservative error assigned to the age (Gradstein *et al.* 2005) overlaps with the end of the Jurassic.

In fact, there is no evidence that anything but the largest HVI events can have global environmental consequences, but several researchers have associated all the above cases with clusters of HVIs (e.g. Napier 2006), so it is worth considering the mechanisms that may cause HVI clusters and evidence for such clusters in the geological record, and their potentially prolonged effects in the environmental record.

Two hypotheses have emerged to explain clusters of HVI craters on Earth. The first is a shower of comets caused by disturbance in the Oort cloud (Hut *et al.* 1987), which modelling indicated would cause an HVI cluster lasting 1–3 Ma. The second hypothesis is of a shower of asteroids from the asteroid

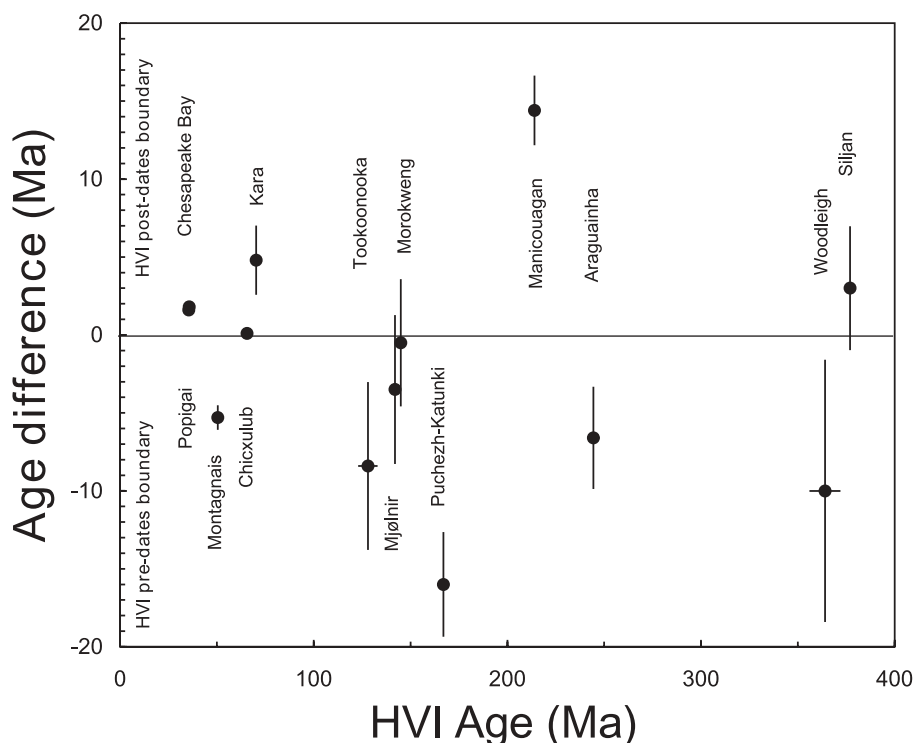


Fig. 5. Age difference between HVI and associated sudden environmental change v. age of a stratigraphic boundary associated with sudden environmental change.

belt between Mars and Jupiter. This hypothesis holds that asteroids can be introduced into resonance bands (known as Kirkwood Gaps) within the asteroid belt by collisions, and by the break-up of larger bodies. Resonance bands are zones where the orbital periods of asteroids are in resonance with Jupiter (the important resonances lie at orbital period ratios of 3:1, 5:2, 7:3 and 2:1 with Jupiter). For example, the 3:1 resonance band contains asteroids with orbital periods one-third that of Jupiter. Such asteroids are therefore more strongly affected by Jupiter's gravity once every three orbits (roughly once every 5 years), their orbits quickly become eccentric and they are ejected from the asteroid belt on time scales of less than 1 Ma. Gladman *et al.* (1997) and Morbidelli & Gladman (1998) showed that many such asteroids fall into the inner Solar System and either fall into the Sun or strike one of the inner planets. Zappala *et al.* (1998) modelled the result of large asteroid body break-ups in the asteroid belt using some of the known asteroid families, and showed that a small percentage would hit the Earth in an apparent cluster of HVIs between 2 and 30 Ma after the break-up event.

There are thus two potential mechanisms capable of delivering showers of HVIs over time scales of 1–30 Ma. Despite the poor preservation record of HVIs, there are several short periods in the terrestrial HVI crater record when the impact rate approaches and even exceeds the steady-state flux based on the present-day value. Perhaps the best documented example is an Ordovician limestone sequence in Sweden that contains fossil L-chondrite meteorites (Schmitz *et al.* 1997) indicating a period of extreme L-chondrite meteorite flux at around 465 Ma (Schmitz *et al.* 2001, 2003) when the estimated flux of small meteorites was around two orders of magnitude greater than the present-day value. Dating of the L-chondrite class of meteorites also yields dates around 465 Ma (McConville *et al.* 1988; Trierloff *et al.* 2003) implying a major collision in the asteroid belt involving a parent body of L-chondrite composition. In addition, Nesvorný *et al.* (2002) showed that the 'Flora' family of asteroids in the main asteroid belt, thought to be the L-chondrites, initiated their unusual orbits less than 1 Ga ago (most asteroid orbits will have been established by at the latest 3.9 Ga). There are also several small HVI craters with ages similar to 465 Ma, many of them in Scandinavia. Although it is tempting to cite these HVI craters as evidence for a HVI crater cluster, the ages themselves are scattered (Schmitz *et al.* 2001) and are not sufficiently precise to confirm synchronicity with the heightened meteorite flux. The number of known craters is no greater than the predicted steady-state value, and, although it is likely that a large break-up event would result in some large HVIs, none of the craters is particularly large.

Another well-documented HVI cluster is the coincidence of two large craters, Popigai (100 km diameter, 35.7 ± 0.2 Ma, Bottomley *et al.* 1997) and Chesapeake Bay (90 km diameter, 35.5 ± 0.3 Ma, Obradovich & Snee 1989), which fell within 200 ka of each other (Whitehead *et al.* 2000). Accompanying the impacts was a heightened flux of extraterrestrial dust detected by monitoring the ^3He content of the non-carbonate fraction of limestones of the same age at Gubbio in Italy. The variation of ^3He showed a slow rise and fall over a period of 2–3 Ma surrounding the two impacts. The combination of large HVIs (two of the largest in the Phanerozoic) and heightened extraterrestrial dust has been interpreted as indicating a comet shower (Mukhopadhyay *et al.* 2001a). Whitehead *et al.* (2000) also suggested that other smaller craters, including Wanapitei (37.2 ± 1.2 Ma) and Mistastin (36 ± 4 Ma), were part of the same cluster as the larger impacts, although it is very difficult to

prove the association as the analytical errors on individual ages are sufficiently large that the cluster does not necessarily exceed the present-day HVI rate. Conversely, given a *c.* 10% preservation rate for HVI craters, it is unlikely that four such craters would be preserved with ages so closely spaced had there not been several more craters now lost through erosion or burial. Recent work on the composition of the bodies that struck the Earth during the late Eocene, based on trace element chemistry of the impact rocks (Tagle & Claeys 2005; Tagle *et al.* 2006), appears to show that the HVIs may not have been the result of a comet shower, but were caused by asteroid bodies with L-chondrite composition. In the light of new trace element evidence for the impacting bodies, higher precision measurements of the ages of smaller craters might not help to constrain the cluster because, as we see from the above discussion, ejections from the main asteroid belt can give rise to HVI clusters lasting over 10 Ma. The same approach can be applied as for large craters and LIPs, to consider how many such clusters may be present in the record and whether they lie close to known times of sudden environmental change based on radiometric dating evidence.

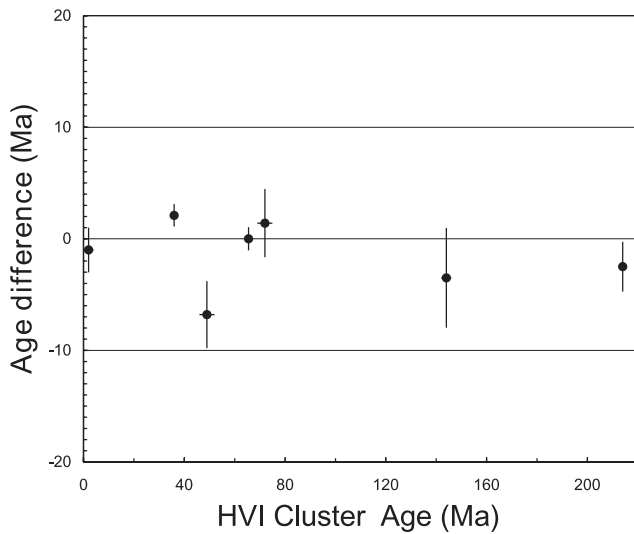
Table 2 is a list of HVI crater clusters in the terrestrial record, and the same data are plotted as age difference between cluster age and boundary associated with sudden environmental change v. HVI cluster age in Figure 6, in the same way as earlier LIP (Fig. 3) and large HVI (Fig. 5) plots. In most cases, three or more craters have been identified, although in one case only two have been identified. Other clusters have been advocated but only seven can be sustained on the basis of radiometric dating, showing evidence of an HVI rate approaching the modern steady-state value. In fact, the youngest cluster is almost certainly an artefact of preservation, with five craters formed in the last 5 Ma. Only one HVI crater in the recent population, the Kara-Kul crater in Tajikistan (52 km), is >20 km in diameter, which may indicate that there are several undiscovered >20 km craters that formed in the last 5 Ma. It should be noted, however, that the age of Kara-Kul is poorly constrained (there is no reported radiometric age). Four of the six earlier clusters overlap with stratigraphic boundaries associated with sudden environmental change, although the errors associated with the crater clusters are large. Two clusters are not associated with boundaries. However, this is a particularly important observation, as the two in question, around 36 Ma and 214 Ma, contain three of the four largest known HVIs in the Phanerozoic era (Popigai, Chesapeake Bay and Manicouagan). Although the study of HVI crater clusters is relatively new, it is clear that radiometric dating shows that clusters do exist in the terrestrial record, but like LIPs and large HVI craters, there is not a one-to-one correlation. Indeed, some of the largest and best constrained clusters are not associated with sudden environmental change. HVI clusters remain an area of active investigation and are open to testing for links with stratigraphic boundaries.

Two potential clusters are not included in Figure 6, one at around 374 Ma and one at 465 Ma. The Siljan crater formed at 376.8 ± 1.7 Ma (Reimold *et al.* 2005), within error of the Frasnian–Famennian boundary (374.5 ± 2.6 Ma). Although there are no other known craters with the same age, there is strong evidence of an increased meteorite flux at the time in the form of tektite horizons (Reimold *et al.* 2005) and an impact-generated melt breccia structure (Leroux *et al.* 1995). The older, Ordovician, potential cluster is associated with strong evidence for heightened flux of L-chondrite bodies (Schmitz *et al.* 2001) but contains no well-dated large crater, and does not correlate closely with a sudden environmental change event.

Table 2. *Clusters of HVI impacts in the geological record*

Cluster age (Ma)	Stratigraphic boundary	Crater name	Age (Ma)	Diameter (km)
2 ± 2	3 ± 0.1	Zhamanshin	0.9 ± 0.1	14
		Bosumptwi	1.1 ± 0.0	10
		Kara-Kul	2.5 ± 2.5	52
		El'gygytyn	3.5 ± 0.5	18
		Bigach	5.0 ± 3.0	8
36 ± 1	33.9 ± 0.1	Chesapeake Bay	35.5 ± 0.3	90
		Popigai	35.7 ± 0.2	100
		Mistastin	36 ± 4	28
		Wanapetei	37.2 ± 1.2	8
		Ragozinka	46 ± 3	9
49 ± 3	55.8 ± 0.2	Gusev	49.0 ± 0.2	3
		Kamensk	49.0 ± 0.2	25
		Montagnais	50.5 ± 0.8	45
		Chicxulub	65.6 ± 0.05	170
		Boltysh	65.2 ± 0.6	25
72 ± 3	70.6 ± 0.6	Ust-Kara, Kara	70.3 ± 2.2	25, 65
		Lappajarvi	73.3 ± 5.3	23
		Manson	73.8 ± 0.3	35
		Mjolnir	142.0 ± 2.6	40
		Gosses Bluff	142.5 ± 0.8	22
144 ± 2	145.5 ± 4	Morokweng	145.0 ± 0.8	70
		Manicougan	214 ± 1	100
		Rochechouart	214 ± 8	23
		St. Martin		

Crater ages and diameters are from the PASSC website and Gradstein *et al.* (2005). It should be noted that several craters are smaller than the 20 km used as a minimum when defining Figures 4 and 5, but in each case there are several craters larger than 20 km are included in the cluster. The smaller ones never define the age of the cluster.

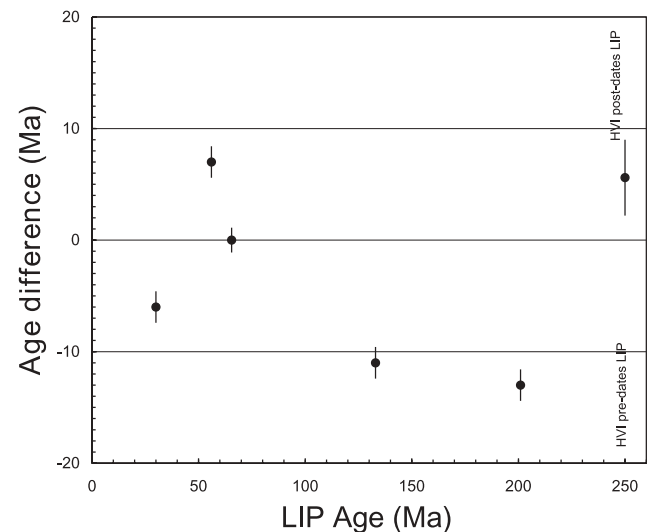
**Fig. 6.** Age difference between HVI cluster and associated sudden environmental change v. age of a stratigraphic boundary associated with sudden environmental change.

The relationship between HVIs and LIPs

There has been considerable debate on the relationship between HVIs and LIPs, in particular an implied causal relationship in which HVIs might lead to LIPs. There has also been a debate concerning modelling of large HVIs in ocean crust, and their potential to initiate mantle decompression and melting (Jones *et al.* 2002; Ivanov & Melosh 2003; Ingle & Coffin 2004), and a

hypothesis concerning the potential of HVIs to initiate the eruption of antipodal LIPs (Glikson 2005).

Figure 7 illustrates the relationship between HVI–LIP age difference (for the closest LIP) and LIP peak eruption ages (neglecting those that are more than 20 Ma apart). There is no fit between HVIs and LIPs in the present database, and, although it can be argued that undiscovered oceanic impacts may be responsible, it seems unlikely that future discoveries will completely change the picture. Previous assignments of HVI–LIP overlaps have been made on the basis of slight overlap or errors,

**Fig. 7.** Age difference between the ages of large HVIs and LIPs v. age of LIP.

and sometimes ages for LIPs are incorrect and no age overlap occurs). The only known case of coincidence is for peak eruption of the Deccan Traps and the large HVI at Chicxulub (Fig. 7). White & Saunders (2005) used a combination of a power law for HVI crater formation (Hughes 1998) and known LIP eruptions to deduce that at least one coincidence of HVI and LIP, and up to three coincidences, would be expected over the last 300 Ma. However, the power-law equation implies more than three Chicxulub-sized HVI impacts every 100 Ma, at least three times the commonly accepted value. Indeed, Hughes (2000) did not use the power-law relationship when estimating HVI cratering rates on Earth, and declared that it was not valid. This is because the number of very large HVIs is so small that the power-law relationship does not adequately describe the probability.

Concluding remarks

The geochronology of large igneous provinces, high-velocity impact craters and stratigraphic boundaries (Gradstein *et al.* 2005) associated with sudden environmental change is sufficiently well constrained to allow testing for coincidence based on the current database of events and their ages. The remaining unknown is the discovery of new large HVI craters. The results show that neither LIPs nor HVIs exhibit one-to-one coincidence with sudden environmental change events and stratigraphic boundaries, and there are several well-characterized cases where major LIPs and HVIs do not coincide with sudden environmental change. These cases are now sufficiently well constrained that it seems unlikely that future work will establish a connection, although recent changes in the ages assigned to stratigraphic boundaries have significantly affected a few correlations.

It is clear that over the last 250 Ma up to six of 15 LIP eruptions have peak eruption ages coinciding to within 1–2 Ma with sudden environmental change. The repeated coincidence has been confirmed by improvement in precision and accuracy of dates on LIPs, but it has also been demonstrated that there have been large LIP eruptions for which no environmental effects have yet been detected. There is a good case, based on geochronology, for a link between LIP eruptions and sudden environmental change, although the precise mechanism remains unclear.

The dating of HVIs is far less mature than that of LIPs and as many as 90% of all HVI impact craters larger than 20 km diameter have been covered or eroded, or are yet to be discovered. Thus, the correlation between known HVIs and times of sudden environmental change is much less evident. Of the 12 largest HVI craters formed in the last 400 Ma, four have ages within error of a boundary associated with sudden environmental change, but three of those are associated with uncertainties of >4 Ma. The case for repeated correlation of HVIs with sudden global environmental change is unproven.

In addition, improved geochronology shows no significant correlation between HVI impacts and LIP eruptions but it does appear to show clusters of HVIs in the geological record. Although the correlation between clusters of HVIs and sudden environmental change is no better than that for large individual HVIs, this field is rapidly changing and the effects of such clusters will depend upon the degree to which the flux of HVIs increases during such clusters.

Finally, the Cretaceous–Palaeogene (KT) boundary remains the only time at which a large HVI (and potential HVI cluster), a large LIP eruption, and well-documented mass extinction coincide.

The Leverhulme Trust is acknowledged for providing funding to pursue

geochronology of HVIs. I would like to thank S. Sherlock for tea and constructive criticism, and the manuscript was improved by reviews by P. Wignall and A. Saunders.

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Received 12 March 2007; revised typescript accepted 13 April 2007.

Scientific editing by Rob Strachan