ELSEVIER

Earth and Planetary Science Letters 205 (2002) 53–62

EPSL

www.elsevier.com/locate/epsl

Extraterrestrial influences on mantle plume activity

Dallas H. Abbott[a,*], Ann E. Isley[b]

[a] *Lamont–Doherty Earth Observatory of Columbia University, Palisades, NY 10964 USA*
[b] *State University of New York at Oswego, Oswego, NY 13126 USA*

Received 12 September 2001; accepted 14 October 2002

Abstract

We use time series analysis to compare the impact histories of the Earth and Moon with the record of mantle plume activity. We use events with errors in their ages of ≤ 150 Ma. The terrestrial and lunar impact records, when smoothed at a 45-Ma interval, correlate at a 97% confidence level. This high confidence level suggests that we have an adequate sampling of most of the major impact events on the Earth. We then test the idea that existing mantle plumes may be strengthened by impacts. When smoothed at a 45-Ma interval, strong plumes correlate with the terrestrial impact record at better than a 99% confidence level. No time lag is discernible between the data sets, which is expected given their present error level. When the time series are smoothed at a 30-Ma interval, there are 10 major peaks in impact activity. Nine out of ten of these peaks have a counterpart in either or both of the strong mantle plume or the mantle plume time series. As a result, the strong mantle plume and the impact time series correlate at the 97% confidence level. The mantle plume and the impact time series correlate at the 90% confidence level. Finally, the Deccan plume showed greatly increased activity immediately after the Chixculub impact. The results of our analysis suggest that large meteorite and cometary impacts may well increase the amount of volcanism from already active mantle plumes.

Keywords: mantle plumes; impact craters; igneous rocks; impacts; komatiites; lunar impacts; time series analysis; mass extinction

1. Introduction

Modern versions of catastrophism propose that catastrophic events significantly influence major Earth processes [1,2]. A key question is whether or not these catastrophes are extraterrestrially or internally driven. Specifically, have meteorite and cometary impacts caused repeated mass extinctions of life on Earth [3,4] or were mass extinctions caused by major episodes of mantle plume volcanism [5,6]? In this paper, we propose a synthesis of these apparently contrary hypotheses: that large meteorite and cometary impacts significantly increase the strength of existing mantle plumes [7], thereby producing their observed correlations with mass extinction events.

---

[*] Corresponding author.
E-mail addresses: dallas@ldeo.columbia.edu (D.H. Abbott), isley@oswego.edu (A.E. Isley).

PII: S0012-821X(02)01013-0

2. The record of impact events and mantle plume events

Both the rock record of mantle plume activity and the cratering record of terrestrial impact events are incomplete. Submarine plume volcanism produces oceanic plateaus and hotspot islands, which may subduct or erode away [8,9]. Subaerial plume volcanism produces extensive flood basalts, which may erode down to their magma chambers and feeder dikes [10,11].

The geological record of impacts striking the Earth is similarly incomplete. During the last 120 million years, an impact large enough to make a 10-km-diameter crater occurred roughly at a rate of 4.3 ± 2.6 per million years [12,13]. This predicted rate of impact cratering is derived from observations of Earth crossing asteroids and comets and also from observations of recent cratering rates on the Moon. This relationship predicts a best estimate of 516 impact craters and a range of 204 to 828 terrestrial impact craters over 10 km in diameter with ages of less than 120 Ma. Of these predicted impact craters and impacting objects, the Eltanin impactor is the only one known that landed on true oceanic crust within the abyssal ocean [14]. The location of the Eltanin crater is unknown. Thus, the known impact craters lie on continental crust: either on the continental shelf, the continental slope, or on subaerial crust.

Using the surface area distribution of the continents [15], roughly 41% of all impactors should land on continental crust. Since 120 Ma, continental impactors should have produced about 212 impact craters, with limiting estimates of between 84 and 339 craters. Yet we know of only about 36 continental craters over 10 km across that formed during the last 120 million years and only about 89 craters over 10 km across that formed during the last 2000 million years [16–18]. This means that we have discovered somewhere between one in two and one in ten continental impact craters. The best estimate is that one in six impact craters that formed on continental crust during the last 120 Ma have been identified.

This paucity of data on both continental and oceanic impact craters means that we must use the record of relatively small craters (>11 km and larger), despite that fact that the total energy of the impact explosion that formed a 11-km crater represents much less energy than the total energy embodied in a mantle plume. We implicitly assume that large cratering events (which are most likely to have occurred in the ocean basins) are accompanied by the formation of many smaller craters, at least a few of which are likely to be preserved on land. This scenario fits with the finding of extraterrestrial amino acids in sediments just above and below the Ir anomaly in K/T boundary sediments [19]. Such amino acids would not be preserved during the impact of a large comet, thus they must be the result of a shower of smaller comets that accompanied the larger impact [20,21].

We compensate for the scarcity of data on impact cratering and mantle plume volcanism in several ways. For plumes, we use four proxies for mantle plume volcanism: (1) flood basalt and oceanic plateau volcanism, (2) massive dike swarms (the feeder dikes), (3) ultramafic and layered intrusions (the magma chambers) and (4) high-MgO extrusives (komatiites, picrites and some ankaramites) [22,23]. In addition to craters, impacts produce indirect effects that are preserved in the geological record. Some impacts produce sedimentary breccias [24,25]. All subaerial impact craters >10 km in diameter should have associated impact melts. If the impact crater is ~ 85 km or more in diameter, the impact melts will be scattered globally in the form of impact spherules [26,27]. Both impact spherules and sedimentary breccias have a size distribution that is directly proportional to the size of their parent impact crater and impacting body [24,28]. By taking into account these indirect effects of plumes and impacts, we were able to compile a more complete record of their occurrence over geological time.

3. Testing the record of large terrestrial impacts

Using known impact craters, impact spherules, and impact breccias, we have assembled an expanded database of terrestrial impacts over geological time. If the impactor has a diameter larger than typical old ocean depths (∼6.4 km) [29], the impact will produce a crater and impact spherules even in the ocean basins [30]. The crater size is between 15 and 30 times the diameter of the impactor [31]. Thus, all impacts that produce > 130 km craters have a very high probability of being recorded as spherule layers within marine sediments. The oldest known terrestrial impact spherules are ∼3.5 Ga [26]. The oldest known, well-dated lunar impact spherules are ∼4.0 Ga [32]. Thus, the impact record of both the Earth and Moon extends far back in their history. We use the lunar database of impacts to test if our terrestrial impact record is reasonably complete, that is, if it records most of the major periods of large meteorite impacts.

Our test of the impact record uses time series analysis. Each age and age error is used to define a Gaussian curve with an area under its curve of one. The individual Gaussian curves are then summed to produce an unweighted time series. We produce a weighted time series of terrestrial impacts by multiplying the individual Gaussians in the data set by the diameter of their respective impact crater and then dividing the resulting Gaussian by the mean diameter of the impact craters in the entire data set. The individual Gaussians are then summed to produce a time series of terrestrial impacts that is weighted by impact crater size.

We also estimated the size of the smallest impact crater that should be considered as a significant event. We did this by using our terrestrial impact database (**Background Data Set**[1], Table 1) and the lunar impact–spherule ages with errors of less than 150 Ma [32] to determine the maximum size of terrestrial impact craters during each well-dated lunar impact event of Phanerozoic age. The largest terrestrial impact craters during these time intervals have inferred diameters that range from 11 to 300 km. Thus, we use terrestrial craters with diameters of 11 km or larger to construct our time series of large terrestrial impact events. Our result is very similar to previous estimates of the smallest size of a significant impact event, i.e., producing impact craters of over 10 km in diameter [33].

The lunar impacts have much larger errors in their ages than the terrestrial impacts [32]. These large errors could significantly bias our test. For this reason, we chose lunar impact spherules with age errors of less than 150 million years. We also smoothed both of the data sets by increasing all age errors less than 45 million years to 45 million years. When this is done, the mean errors of the terrestrial impact ages become comparable to those of the lunar ages (Table 1).

The lunar test of the terrestrial impact record uses a cross-correlation analysis between the two impact time series. The two time series, both smoothed at 45-Ma intervals, correlate at a 97% confidence level and have a time lag of about 4 Ma (Table 2, Fig. 1). Because the sum of the mean error of both time series is larger than 4 Ma (Table 1), the effective time lag is zero. Thus, the cross-correlation results suggest a similar impact history for the Earth and Moon over the last 3.8 Ga, as would be expected for two planetary bodies in such proximity [34].

This result implies that our technique of assembling impact data for the Earth has correctly identified most of the major impact events on the Earth.

Table 1
Errors in input data for each time series

Time series	Smoothing age Ma	Mean age error Ma
Mantle plume	30	36
Lunar spherule	30	72
Terrestrial impact	30	33
Strong plume	30	36
Mantle plume	45	48
Lunar spherule	45	76
Terrestrial impact	45	46
Strong plume	45	49

Smoothing age represents the minimum age error that was artificially set for each time series. Any age with an error less than the smoothing age was reset to the minimum age error.

---

[1] http://www.elsevier.com/locate.epsl

4. Impact effects on mantle plume volcanism

The hypothesis that large impacts can strengthen existing mantle plumes may be tested in two ways: by looking at the overall abundance of mantle plume activity versus the abundance of large impacts and by looking at the temporal incidence of the strongest mantle plumes versus the temporal occurrence of large impacts. If large impacts do strengthen existing mantle plumes, both the overall abundance of plume magmatism and the abundance of very strong mantle plumes should increase as large impacts increase.

The strength of a mantle plume is defined by its overall excess temperature anomaly [35]. Hotter plumes produce more melting in the mantle, thus resulting in more voluminous extrusive volcanism and more high-Mg rocks [36,37]. We use the ages of high-Mg rocks as a proxy for times of strong mantle plume volcanism. The selected rocks must have MgO contents above 10%, and be derived from a komatiitic parent (MgO $>18\%$). These are not just high-Mg extrusives, such as ankaramites, komatiites, and picrites, but also high-Mg intrusives within massive dike swarms and layered intrusions [22]. By using all of these rock types, we identify strong mantle plume activity in terranes with different erosional levels.

We tested the effect of large impacts on mantle plume volcanism by performing a cross-correlation analysis of all mantle plume volcanism and strong mantle plume volcanism versus the impact record. All input age dates were smoothed by setting the minimum age error to 45 million years (Fig. 1) and 30 million years (Fig. 2).

We also tried smoothing the data by setting the minimum age error to 15 million years. The cross-correlation results for plumes and strong plumes versus impacts had confidence levels of 79% and 80%, respectively. This is better than random chance (50% confidence level), but is not statistically significant. Because the unsmoothed plume time series has a mean age error of 8 Ma, the low significance level of the cross-correlations that use the 15 Ma smoothing might seem surprising. We attribute these poor results to the overall paucity of data on large impact events. We have only 73 known large impact events for an average of one event every 51 million years! Thus, we need to compensate for the poorly known impact record by smoothing the data to a large extent.

The impact record smoothed at 30 Ma has ten prominent peaks. Nine out of ten of these peaks have counterparts in the strong mantle plume and/or the mantle plume time series. This match of peaks is reflected in the 97% confidence level of the cross-correlation between the strong plume and the impact time series and the 90% confidence level of the cross-correlation between the plume and the impact time series. The confidence levels of the cross-correlations increase to 99% (strong plumes) and 96% (plumes) for time series that are smoothed at a 45-Ma interval (Table 2). In all cases, the best-fit time lags between the time series are less than twice the smoothing interval, that is effectively zero. Thus, a higher abundance of large

Table 2
Cross-correlation results

Time series cross-correlated	Correlation coefficient	Confidence level %	Time lag Ma	Smoothing age Ma
Terrestrial impacts vs. lunar impacts	0.71	97	4	45
All plumes vs. terrestrial impacts	0.69	96	23	45
Strong plumes vs. terrestrial impacts	0.77	99	42	45
Terrestrial impacts vs. lunar impacts	0.67	90	2	30
All plumes vs. terrestrial impacts	0.64	90	23	30
Strong plumes vs. terrestrial impacts	0.70	97	33	30

Correlation coefficients have a range of significance levels because each time series has different spectral characteristics. Confidence levels are calculated by comparison with the correlation coefficients between each time series and 1000 randomly generated time series with the same spectral characteristics [23]. The time lag is the time difference between the two time series that results in the highest value of the correlation coefficient.

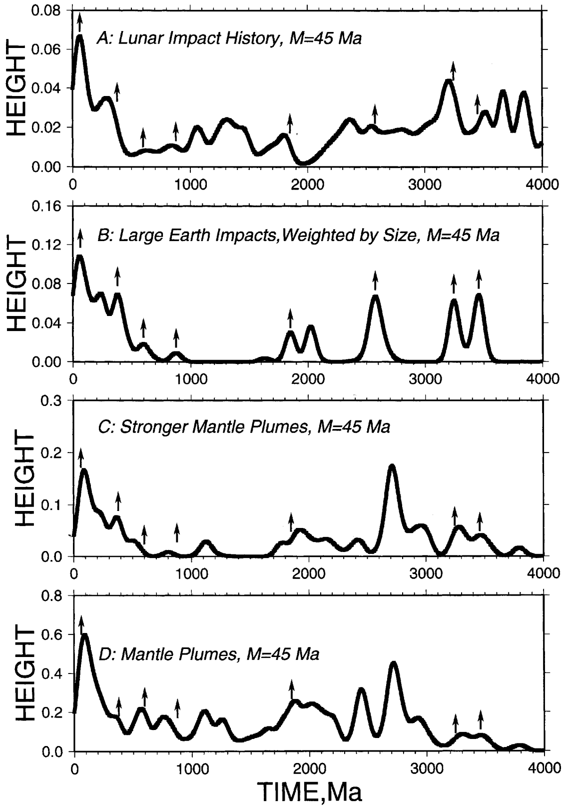

Fig. 1. Height of time series versus age in Ma. All data is smoothed by adjusting the minimum age error (M) to 45 Ma. (A) Lunar impact history as derived from dating of impact spherules with age errors of ≤150 Ma. Arrows are at the same point in time as the tops of peaks in large impacts. Note that, within the mean error of the ages in the lunar time series (76 Ma, Table 1), these peaks line up. (B) Terrestrial impact history derived from dating of known impact craters and inferred impact craters with diameters greater than 11 km. The peak heights in the time series are weighted by the size of the inferred impact crater for each impact event. Note the arrows denoting peaks that line up in the terrestrial and lunar impact time series. These arrows are throughout the time series, supporting the 97% confidence level of the cross-correlation between the two time series. (C) Stronger mantle plumes derived from dating of high-MgO extrusives and intrusives through time. Note the arrows showing seven peaks that line up throughout geological time in series B, C and D, supporting the 96 to 99% confidence level of the cross-correlation between the two plume time series and the terrestrial impact time series. (D) All mantle plumes as derived from dating of the four mantle plume proxies: massive dike swarms, high-Mg extrusives, flood basalts, and ultramafic and mafic layered intrusions. Arrows are at the same point in time as the tops of peaks in large impacts that line up with peaks in the lunar impact record. Note that seven out of eight peaks line up within the mean error of the ages in the terrestrial impact time series (46 Ma, Table 1). Note also that some of the Meso-Proterozoic and Early Archean peaks in the lunar time series appear to line up with peaks in the two plume time series, suggesting that there are major terrestrial impact events that remain to be discovered.
←

impacts correlates well with stronger mantle plumes and more mantle plumes in general.

By smoothing the impact record at 45 and 30 million-year intervals, we essentially added together closely spaced peaks from large impacts or from single mantle plumes into a single peak in activity. We did this more explicitly by adding together the area under each time series curve at 250 million-year intervals (Fig. 3). This area method (e.g., spectral energy method) gives more weight to the largest impacts than does a simple count of the number of large impacts in each 250 million-year interval.

The resulting curves of total area versus time show four large peaks in terrestrial impact activity that are directly matched by peaks in mantle plume and strong mantle plume activity (Fig. 3). The matching peaks are at 125, 1875, 2625, and 3375 Ma. There are also two prominent lulls in impact activity, one in mid-Proterozoic time and the second at about 2.4 Ga. These lulls in impact activity are well-reproduced in the activity of strong mantle plumes, less so by the activity of mantle plumes in general. Nevertheless, the overall patterns show striking parallels in activity peaks and lows, and in the activity trends of mantle plumes and large impacts.

If mantle plumes (and mass extinctions) are being influenced by large impacts, their time series should have similar spectral characteristics. The spectral periods proposed for impacts (and mass extinctions) are between 26 and 36 Ma [38]. In order to resolve the shortest period, the mean age error of the data analyzed must be less than 13% of the period or less than 3.4 Ma [39]. This means that we must use events dated to within ±9 Ma for our spectral analysis.

There are 38 large impacts with ages between 0 and 256 million years whose age errors are less

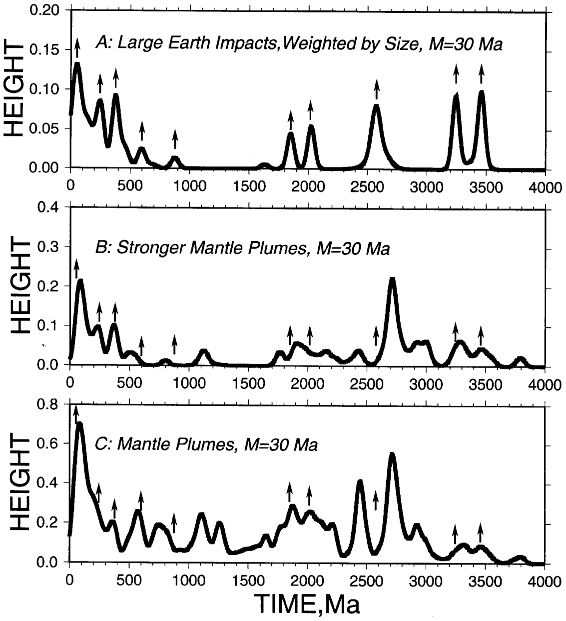

Fig. 2. Height of time series versus age in Ma. All data is smoothed by adjusting the minimum age error (M) to 30 Ma. (A) Terrestrial impact history derived from dating of known impact craters and inferred impact craters with diameters greater than 11 km. The peak heights in the time series are weighted by the size of the inferred impact crater for each impact event. Note the arrows denoting peaks that line up. These arrows are throughout the time series, supporting the high confidence levels of the cross-correlations among the time series. (B) All mantle plumes as derived from dating of the four mantle plume proxies: massive dike swarms, high-Mg extrusives, flood basalts, and ultramafic and mafic layered intrusions [22,48,49]. Arrows are at the same point in time as the tops of peaks in large impacts. (C) Stronger mantle plumes derived from dating of high-MgO extrusives and intrusives through time. Note the arrows showing that nine out of ten prominent peaks in the impact time series also appear in either or both of the plume and strong plume time series.

than 10 million years. Twenty-nine of these well-dated impacts have ages between 0 and 128 million years. The spectrum of large impacts (weighted by size) between 0 and 256 million years in age has its highest peak at 85 million years and its second highest peak at 36 million years (Fig. 4). The spectrum for all mantle plume events between 0–256 Ma also has two peaks, both of nearly equal height. The highest peak is at 64 million years, and the next highest peak is at 32 to 36 million years. The spectrum for strong mantle plumes has a single peak at 32 to 36 million years. There is no significant peak at longer periods. Because only 9 out of 38 large well-dated impacts are between 128 and 256 Ma in age, we also calculated the spectrum for impacts (weighted by size) between 0 and 128 Ma in age. The 0–128 Ma spectrum has a single dominant peak at 32 Ma, very similar to the spectrum for strong mantle plumes from 0 to 256 Ma in age.

5. Discussion: impacts and strengthening of plumes

The overall results of the cross-correlation and spectral analysis provide three sets of evidence that we believe strongly support a temporal relationship between large impacts and resultant

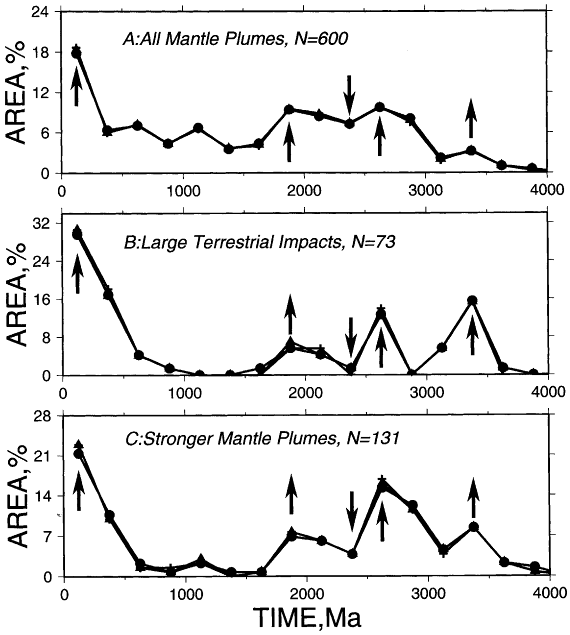

Fig. 3. Area under three sets of curves and three sets of data summed at 250 Ma intervals for the period 0 to 4000 Ma. The three sets of curves were derived from data with minimum errors set to 45 Ma (triangles), 30 Ma (circles), and 15 Ma (crosses). In most cases, the three curves are so close that only the 30 Ma circles show clearly on the plot. Arrows show four matching peaks and one trough that appear in all three data sets. (A) All mantle plumes, 600 ages (N) and age errors used. (B) Large (>11-km-diameter crater) terrestrial impact events, time series uses 73 ages (N) and inferred crater sizes. (C) Stronger mantle plumes, 131 ages (N) used.

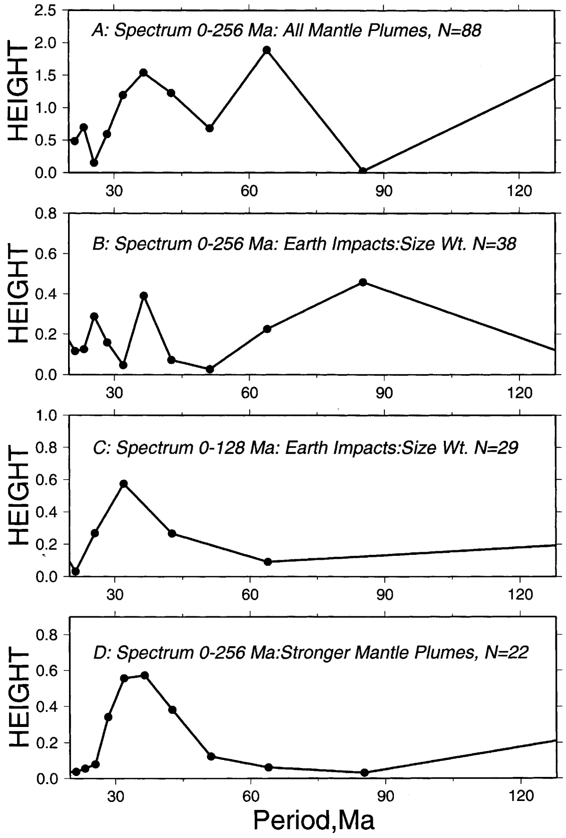

Fig. 4. Age versus height from spectral analysis. Spectra used Matlab spectrum command. Data were demeaned and filtered using a Hanning window. All data sets have maximum age errors of 10 million years. (A) All well-dated mantle plume events for 0–256 Ma (88 total). (B) All well-dated terrestrial impacts, weighted by crater size, from 0–256 Ma (38 total). (C) All well-dated terrestrial impacts, weighted by crater size from 0–128 Ma (29 total). (D) All well-dated stronger mantle plume events for 0–256 Ma (22 total).

strengthening of mantle plumes. The first is the high confidence levels (between 90 and 99%) and the zero effective time lag of the cross-correlations between mantle plumes and large impacts for the last 4.0 Ga. The second is the high confidence levels (between 97 and 99%) and zero effective time lag of the cross-correlations between strong mantle plumes and large impacts for the last 4.0 Ga. The third is the similarities in the spectrum of mantle plumes and impacts, both of which show strong spectral peaks at 32 to 36 million years. All of these are bolstered by the coincidence of individual peaks, both in the time series records (Figs. 1 and 2) and in the 0 to 4.0 Ga summed record (Fig. 3). Thus, we can definitely say that stronger mantle plumes do occur at the same times in Earth history during which there are more large impacts, but the large age errors do not allow us to prove a cause and effect relationship between large impacts and a resultant strengthening of mantle plumes.

There is observational evidence that supports a cause and effect relationship between large impacts and strengthening of existing mantle plumes. The best documented is the temporal relationship between the K/T boundary impact at Chixculub and the major phase of Deccan trap volcanism. The Deccan traps were active well before the K/T boundary impact [40]. However, the most voluminous phase of Deccan trap volcanism occurred immediately after the impact, during chron 29R, which follows immediately after K/T boundary time [6]. This volcanic phase produced the bulk of the Deccan traps and lasted less than 1 million years. Thus, the Deccan plume was strongest immediately after the Chixculub impact.

6. Impacts, plumes and mass extinctions

Because our best estimate is that scientists have discovered only one out of six of the large impacts on land, it is not particularly surprising that only one of the big six Phanerozoic mass extinctions has a mapped, extremely large impact crater (the K/T boundary crater at Chixculub). There are new data suggesting that an extraterrestrial impact produced the largest mass extinction of all, the Permo-Triassic extinction [41]. The impact was presumably oceanic, and is estimated to have formed a crater from 300 to 600 km in diameter [42]. There is also equivocal data suggesting that an impact produced the end-Triassic mass extinction [43].

Our data set shows a large peak in impact occurrence at another major extinction boundary, the Frasnian–Famennian boundary at ~380 Ma (Fig. 1B, (**Background Data Set**[1], Table 1). However, the largest Frasnian–Famennian impact deposit yet found came from a crater that was only about 120 km in diameter [44]. This is not surprising, given that 59% of the Earth's surface is covered by ocean and that about five out of six large Phanerozoic-age impact craters on land remain to be discovered. We conclude, therefore, that the level of evidence supporting a connection between large impacts and mass extinctions is about what would be expected (or better), given the available data on impacts.

7. Mechanism for strengthening of plumes by large impacts

The biggest mystery is the mechanism by which large impacts might intensify existing mantle plumes. We propose three, non-exclusive mechanisms, but other mechanisms may be equally plausible. The first is that impacts may cause cracking and de-stressing of the crust, allowing melts that had been trapped due to tectonic stress and/or impermeable boundaries to rise more easily to the surface. The second is that impacts may produce large cracks in the surface of the Earth, allowing new plate boundaries to form with consequent thinner lithosphere and longer melt columns. The third is that impacts may produce microdikes at the core mantle boundary. If dikes are very thin, capillary forces can promote mixing of molten core and mantle material like that seen in pallasitic meteorites. This would greatly increase the amount of heat available for melting the mantle, and could produce a rapid intensification of existing mantle plumes after a large meteorite impact. This latter process could also explain the core component within some strong mantle plumes [45–47].

Further testing of these ideas can be done in several ways: (1) by comparing the recent record of plate boundary reorganization to the times of occurrence of large impacts, (2) by comparing the compositions of the more voluminous later plume magmas with the less voluminous earlier phases of the Siberian Traps and the North Atlantic Tertiary Province event, analyzing them specifically for their relative abundance of core component, and (3) by comparing the volumes of recent episodes of increased arc volcanism versus the temporal record of impact events. Tests 1 and 3 require a much more detailed and well-dated history of recent large impacts, in particular oceanic impacts. Only one abyssal ocean impact in the last 200 million years is currently known, the Eltanin impact. (The Chixculub impact and others like it were on the continental shelf.)

8. Conclusions

Several lines of evidence point to a temporal relationship between large meteorite and cometary impacts and stronger mantle plume activity. Time series of mantle plumes and strong mantle plumes from 0 to 3.8 Ga correlate with a time series of large meteorite impacts at high confidence levels with a zero effective time lag. Using 250-Ma intervals, there are four large-scale peaks in plume activity over the last 3.8 Ga that are directly correlated with large-scale peaks in impact intensity. There are also prominent lulls in impact activity during the Meso-Proterozoic and at about 2.4 Ga that are duplicated in the record of strong mantle plume activity. Spectral analyses of the data for all mantle plumes, for strong mantle plumes, and for meteorite impacts produce large spectral peaks at 32–36 Ma, coincident with the interval for passage of the solar system through the galactic plane. Finally, at least one large impact, the 0.065 Ga Chixculub event, produced a consequent intensification of its associated mantle plume, producing the chron 29R portion of the Deccan traps. This latter evidence points to a direct cause-and-effect relationship between impacts of large meteorites or comets and a consequent strengthening of existing mantle plumes.

Acknowledgements

We thank S. Hoffman for editing. We thank A. Glikson, B. Simonsen, and S. Hassler for copies of papers that were in press. We thank A. Glikson, M. Rampino, R. Stothers, and J. Plado for reviews. We thank A. Nunez and C. Glatz for careful proofreading. We thank our librarian,

M. Bruckner, for obtaining many obscure papers and books for us. J. Plado and L. Pesonen graciously provided us with copies of their 2000 impact conference proceedings. R. Grieve and his research group maintain a website about confirmed impact craters and their diameters. This website greatly speeded our searches of the impact literature by providing us with the names and diameters of all but the most recently discovered impact craters. LDEO contribution 6392.***[BOYLE]***

References

[1] A.Y. Glikson, Mega-impacts and mantle-melting episodes: tests of possible correlations, in: Y. Glikson Andrew (Ed.), Thematic Issue: Australian Impact Structures, AGSO J. Aust. Geol. Geophys. 16 (1996) 587–607.

[2] A.Y. Glikson, The astronomical connection of terrestrial evolution: crustal effects of post-3.8 Ga mega-impact clusters and evidence for major 3.2 ± 0.1 Ga bombardment of the Earth–Moon system, J. Geodyn. 32 (2001) 205–229.

[3] M.R. Rampino, B.M. Haggerty, The 'Shiva hypothesis': impacts, mass extinctions, and the galaxy, Earth Moon Planets 72 (1996) 441–460.

[4] L.W. Alvarez, W. Alvarez, F. Asaro, H.V. Michel, Extraterrestrial cause for the Cretaceous–Tertiary mass extinction, Science 208 (1980) 1095–1108.

[5] P.R. Vogt, Evidence for global synchronism in mantle plume convection, and possible significance for geology, Nature 240 (1972) 338–342.

[6] V. Courtillot, J.J. Jaeger, Z. Yang, G. Feraud, C. Hofmann, The influence of continental flood basalts on mass extinctions: where do we stand?, in: G. Ryder, D. Fastovsky, S. Gartner (Eds.), The Cretaceous–Tertiary Event and Other Catastrophes in Earth History, Special Paper 307, Geological Society of America, Boulder, CO, 1996, pp. 513–525.

[7] J.T. Hagstrum, B.D. Turrin, Island flood basalt volcanism: a seismically induced response to large antipodal bolide impacts?, EOS Trans. AGU 72 (1991) 516.

[8] D.H. Abbott, R. Drury, W. Mooney, Continents as lithological icebergs: the importance of buoyant lithospheric roots, Earth Planet. Sci. Lett. 149 (1997) 15–27.

[9] P. Mann, L. Gahagan, M. Coffin, T. Shipley, S. Cowley, E. Phinney, Regional tectonic effects resulting from the progressive east-to-west collision of the Ontong Java Plateau with the Melanesian Arc system, EOS Trans. AGU 77 (1997) 712.

[10] A.N. LeCheminant, L.M. Heaman, Hotspot origin for giant radiating dyke swarms: evidence from the MacKenzie igneous events, Canada, in: Anonymous (Ed.), Continental Magmatism: Abstracts. Bulletin New Mexico Bureau of Mines and Mineral Resources, Socorro, NM, 1989, 160 pp.

[11] A. Gudmundsson, Emplacement of dikes, sills and crustal magma chambers at divergent plate boundaries, Tectonophysics 176 (1990) 257–275.

[12] E.M. Shoemaker, Asteroid and comet bombardment of the Earth, Annu. Rev. Earth Planet. Sci. 11 (1983) 461–494.

[13] H.R. Shaw, Craters, Cosmos, and Chronicles. Stanford University Press, Stanford, CA, 1994, 688 pp.

[14] R. Gersonde, F.T. Kyte, U. Bleil, B. Diekmann, J.A. Flores, G. Grahl, R. Hagen, G. Kuhn, F.J. Sierros, D. Volker, A. Abelmann, J.A. Bostwick, Geological record and reconstruction of the late Pliocene impact of the Eltanin asteroid, Nature 390 (1997) 357–363.

[15] J.G. Cogley, Continental margins and the extent and number of continents, Rev. Geophys. Space Phys. 22 (1984) 101–122.

[16] R.A.F. Grieve, L.J. Pesonen, Terrestrial impact craters: their spatial and temporal distribution and impacting bodies, Earth Moon Planets 72 (1996) 357–376.

[17] R.A.F. Grieve, M. Pilkington, The signature of terrestrial impacts, AGSO J. Aust. Geol. Geophys. 16 (1996) 399–420.

[18] R.A.F. Grieve, J. Rupert, A. Therriault, Impact Structures. http://www.unb.ca/passc/impactDatabase/CINameSort.html.

[19] M. Zhao, J.L. Bada, Extraterrestrial amino acids in Cretaceous/Tertiary boundary sediments at Stevns Klint, Denmark, Nature 339 (1989) 463–465.

[20] N.C. Wickramasinghe, M.K. Wallis, A Jupiter fragmented comet: cause of the K/T boundary record, in: H. Rickman, J. Valtonen Mauri (Eds.), Worlds in Interaction: Small Bodies and Planets of the Solar System, Earth, Moon, and Planets 72 (1996) 1–3/Kluwer Academic, Dordrecht, 1996, pp. 461–466.

[21] K. Zahnle, D.H. Grinspoon, Comet dust as a source of amino acids at the Cretaceous/Tertiary boundary, Nature 348 (1990) 157–160.

[22] A.E. Isley, D.H. Abbott, Implications of the temporal distribution of high-Mg magmas for mantle plume volcanism through time, J. Geol. 110 (2002) 141–158.

[23] A.E. Isley, D.H. Abbott, Plume-related mafic volcanism and the deposition of banded iron-formation, J. Geophys. Res. 104 (1999) 15461–15477.

[24] J.E. Warme, H.C. Kuehner, Anatomy of an anomaly: the Devonian catastrophic Alamo impact breccia of southern Nevada, Int. Geol. Rev. 40 (1998) 189–216.

[25] J.R. Morrow, C.A. Sandberg, W. Ziegler, Recognition of early late Devonian impacts: Alamo, Nevada and Amonau, Germany, Geol. Soc. Am. (Abstr. Programs 31 (1999) 64.

[26] D.R. Lowe, G.R. Byerly, F. Asaro, F.J. Kyte, Geological and geochemical record of 3400 million year old terrestrial meteorite impacts, Science 245 (1989) 959–962.

[27] B.R. Simonson, S.W. Hassler, N.J. Beukes, Late Archean impact spherule layer in South Africa that may correlate

with a Western Australian layer, in: O. Dressler-Burkhard, V.L. Sharpton (Eds.), Large Meteorite Impacts and Planetary Evolution, Special Paper 339, Geological Society of America, Boulder, CO, 1999, pp. 249–261.

[28] S.W. Hassler, H.F. Robey, B.M. Simonsen, Bedforms produced by impact-generated tsunami, ~2.6 Ga Hamersley basin, Western Australia, Sediment. Geol. 135 (2000) 283–294.

[29] C.A. Stein, S. Stein, A model for the global variation in oceanic depth and heat flow with lithospheric age, Nature 359 (1992) 123–129.

[30] B.M. Simonsen, P. Harnik, Have distal impact ejecta changed through geologic time?, Geology 28 (2000) 975–978.

[31] D.W. Hughes, The mass distribution of crater producing bodies, in: M.M. Grady, R. Hutchinson, G.J.H. McCall, D.A. Rothery (Eds.), Meteorites: Flux with Time and Impact Effects, 140. Geological Society of Britian, London, 1998, pp. 31–42.

[32] T.S. Culler, T.A. Becker, R.A. Muller, P.R. Renne, Lunar impact history from 40Ar/39Ar dating of glass spherules, Science 287 (2000) 1785–1788.

[33] D.M. Raup, Extinction: Bad Genes or Bad Luck? W.W. Norton and Company, New York, 1991, 210 pp.

[34] H. Frey, Crustal evolution of the Early Earth: the role of major impacts, Precambrian Res. 10 (1980) 195–216.

[35] N.H. Sleep, Hotspots and mantle plumes: some phenomenology, J. Geophys. Res. 95 (1990) 6715–6736.

[36] D. McKenzie, M.J. Bickle, The volume and composition of melt generated by extension of the lithosphere, J. Petrol. 29 (1988) 625–679.

[37] C. Herzberg, M.J. O'Hara, Phase equilibrium constraints on the origin of basalts, picrites, and komatiites, Earth Sci. Rev. 44 (1998) 39–79.

[38] M.R. Rampino and R.B. Stothers, Periodicity in extinctions and impacts: where do we stand after 15 years?, in: Anonymous (Ed.), Geological Society of America, 1999 Annual Meeting, Abstracts with Programs, 31, 7. Geological Society of America, Boulder, CO, 1999, 398 pp.

[39] J. Heisler, S. Tremaine, How dating uncertainties affect the detection of periodicity in extinctions and craters, Icarus 77 (1989) 213–219.

[40] S. Bhattacharji, N. Chatterjee, J.M. Wampler, P.N. Nayak, S.S. Deshmukh, Indian intraplate and continental margin rifting, lithospheric extension and mantle upwelling in Deccan flood basalt volcanism near the K/T boundary: evidence from mafic dike swarms, J. Geol. 104 (1996) 379–398.

[41] L. Becker, R. Poreda, Extraterrestrial impact at the 250 myr old Permian-Trassic boundary, EOS Trans. AGU 81 (2000) Fall Meet. Suppl. Abstr. B61B–13.

[42] K. Kaiho, Y. Kajiwara, T. Nakano, Y. Miura, H. Kawahata, M. Ueshima, Z. Chen, G.R. Shi, End-Permian catastrophe by a bolide impact: evidence of a gigantic release of sulfur from the mantle, Geology 29 (2001) 815–818.

[43] P.E. Olsen, C. Koeberl, H. Huber, A. Montanari, S.J. Fowell, Geochemical and biological evidence for a catastrophic end to the Triassic, EOS Trans. AGU 81 (2000) Fall Meet. Suppl. Abstr. V72E–11.

[44] A.J. Mory, R.P. Iasky, A.Y. Glikson, F. Pirajno, Woodleigh, Carnarvon Basin, Western Australia; a new 120-km diameter impact structure, Earth Planet. Sci. Lett. 177 (2000) 119–128.

[45] I.S. Puchtel, G.E. Bruegmann, A.W. Hofmann, (super 187) Os-enriched domain in an Archean mantle plume: evidence from 2.8 Ga komatiites of the Kostomuksha greenstone belt, NW Baltic Shield, Earth Planet. Sci. Lett. 186 (2001) 513–526.

[46] A.C. Kerr, J. Tarney, G.F. Marriner, G.T. Klaver, A.D. Saunders, M.F. Thirwall, The geochemistry and petrogenesis of the Late-Cretaceous picrites and basalts of Curacao, Netherlands Antilles: remnant of an oceanic plateau, Contrib. Mineral. Petrol. 124 (1996) 29–43.

[47] A.C. Kerr, J. Tarney, G.F. Marriner, A. Nivia, A.D. Saunders, The Caribbean–Colombian Cretaceous igneous province: the internal anatomy of an oceanic plateau, in: J.J. Mahoney, M.F. Coffin (Eds.), Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism, Geophysical Monograph 100. American Geophysical Union, Washington DC, 1997, pp. 123–144.

[48] D.H. Abbott, A.E. Isley, The duration, magnitude, and intensity of mantle plume activity over the last 3.8 Ga, J. Geodyn. 34 (2002) 265–307.

[49] R.E. Ernst, K.L. Buchan, Large mafic magmatic events through time and links to mantle plume heads, in: R.E. Ernst, K.L. Buchan (Eds.), Mantle Plumes: Their Identification Through Time, Special Paper 352. Geological Society of America, Boulder, CO, 2001, pp. 483–566.