Rubey Colloquium Paper

Comparing the Evidence Relevant to Impact and Flood Basalt at Times of Major Mass Extinctions

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ABSTRACT

The five major mass extinctions identified in 1982 by Raup and Sepkoski have expanded to six, with the suggestion that the Permian-Triassic extinction was a double event. Is there a general explanation for great mass extinctions, or can they result from different triggers, or even from internal system instabilities? The two most-discussed candidates for a general extinction mechanism are impacts and flood-basalt eruptions. A compilation of evidence for impact at the times of mass extinctions shows that this cause is abundantly confirmed in the case of the Cretaceous-Tertiary extinction and the late Eocene, which is a time of minor and gradual extinction, but little or no evidence connects other major extinctions to impact. On the other hand, there is a remarkable time correlation between flood basalts and four major extinctions, but no other evidence that flood basalts cause mass extinctions. The evidence for an impact–extinction linkage is strikingly different from that for a connection between flood basalts and extinctions. Flood basalts cover larger areas than craters and their associated thick ejecta blankets, which are thus less likely to be found. Impacts distribute proxies globally at instantaneous time horizons, whereas flood-basalt events are extended in time, and no remote proxies have been recognized. Many global killing mechanisms have been proposed in the case of impacts, but few have been suggested for flood basalts. It is possible that flood basalts are triggered by impact, but it is not obvious how impacts could result from anything other than chance. The hypothesis that impacts are the general cause of mass extinctions has not received supporting evidence, but has not been falsified. The hypothesis that flood basalts are the general cause of mass extinctions is supported by evidence from timing, but is not susceptible to falsification. Other candidates for general extinction causes, especially sea-level changes and system instabilities, would require separate treatment. The question is still very much open. Key Words: Mass extinction—Impact—Volcanism—Killing mechanism. Astrobiology 3, 153–161.

INTRODUCTION

Much research activity in the field of impacts and mass extinctions has been focused on the Cretaceous-Tertiary (KT) mass extinction and the impact that produced the crater in the subsurface of the Yucatán Peninsula at that time. It is important also to take a broader look at the entire set of five or six major extinctions and address the question whether there is a com-
mon cause for them all, or whether there are different causes for different events. Today, as for the last 20 years, two principal contenders for recognition as a general cause of mass extinctions are, on the one hand, the impacts of comets or asteroids, and, on the other, volcanism, and specifically flood-basalt volcanism. [For sea-level change, a third long-time contender not considered here, see Hallam (1989) and Hallam and Wignall (1997, 1999).] It is not yet possible to give a reliable answer to the general question of extinction causes, but in the meantime it is useful to look at some of the problems that confront us as we try to obtain an answer.

Recently an interesting case has been made that flood basalts may be the general cause of mass extinctions, with impact a complicating factor in the KT case (Wignall, 2001). If it turns out that the evidence for a flood basalt–extinction link is compelling, we must of course accept that conclusion. Indeed, one might argue that finding a different cause of one or more mass extinctions would be more interesting than demonstrating that impacts caused them all. However, before accepting volcanism as the cause of one or several mass extinctions, we should carefully examine the support for that hypothesis. The evidence linking the KT extinction to impact was challenged in excruciating detail throughout the 1980s; evidence linking flood-basalt eruptions to mass extinctions should not be treated more gently.

**EVIDENCE**

We can formulate the problem of evidence as two questions: (1) What evidence is there that impacts cause extinctions? (2) What evidence is there that flood-basalt volcanism causes mass extinctions? In looking at the current evidence, we find that there are striking dissimilarities, or asymmetries, between the two cases. The most prominent asymmetry is that there is abundant evidence that impact is responsible for one mass extinction, the one at the KT boundary, but little or no evidence connecting impact to any of the other major extinction events, while, on the other hand, there is a remarkable time correlation between flood basalts and four of the major extinctions, but no other evidence of a connection. Additional asymmetries between flood basalts and impacts will be considered later, but we can begin with a brief review of the evidence.

**Mass extinctions**

Beginning with Raup and Sepkoski’s compilation and analysis of the stratigraphic ranges of families (Raup and Sepkoski, 1982; Sepkoski, 1982), it has been widely accepted that five major extinctions have occurred since \( \sim 570 \) Ma, when fossils became abundant enough to leave a detailed stratigraphic record: \( \sim 65 \) Ma, KT; \( \sim 200 \) Ma, Triassic-Jurassic (TJ); \( \sim 250 \) Ma, Permian-Triassic (PT); \( \sim 365 \) Ma, Frasnian-Fammenian (FF), within the Late Devonian; and \( \sim 440 \) Ma, Ordovician-Silurian (OS).

About five other, secondary extinctions stand out above background extinction rates in that study. Recently the list of major events has changed slightly, because of the suggestion that the PT event, the greatest of all extinctions, actually comprises two major extinction pulses close together. The earlier one would have occurred at the Capitanian-Wuchiapingian (CW) boundary, which is also the boundary between the Middle and the Upper Permian, and the later one at the PT boundary (Jin et al., 1994; Stanley and Yang, 1994).

As one looks farther back in time, the amount of sedimentary record diminishes, but this general trend is complicated by the details of outcrop availability at each extinction. The most recent event, at the KT boundary, is by far the best known, but because of scarce record, the PT boundary is probably more poorly known than the substantially older FF event. Sediments in oceanic basins, a major source of data on the KT event, are unavailable for the five older mass extinctions because of the complete subduction of oceanic basins older than \( \sim 180 \) Ma.

**Flood basalts**

A recent review paper about the correlation in ages between mass extinctions and flood basalts (Wignall, 2001) makes it unnecessary to go over the evidence here. The critical point emerging from that review is that there are four correlated pairs of extinctions and flood basalts: Deccan Traps (India), KT extinction; Central Atlantic Magmatic Province (CAMP), TJ extinction; Siberian Traps, PT extinction; and Emeishan basalts (southwestern China), CW extinction.

There is also a possibility that an earlier, Middle Paleozoic, flood-basalt event in eastern Siberia (Zolotukhin and Al’Mukhamedov, 1988) correlates with the FF mass extinction (V. Courtillot, personal communication, 2001).
To me it is particularly impressive that the Emeishan basalts were found to be close in age to the CW event at just about the time the CW event was being recognized as distinct from the PT event (Wignall, 2001).

This is certainly a remarkable set of time correlations, and one can scarcely fail to take it seriously. However, as Wignall (2001) states, “By far the most compelling evidence for a link between volcanism and extinctions comes from the comparison of the ages of flood basalt provinces and mass extinction events. . . .” In fact, there seems to be no other evidence for a causal connection, a point I will discuss below.

**Impact**

The situation regarding impacts is completely different. In this case there is overwhelming evidence for a causal connection between the Chicxulub impact and the KT mass extinction, but evidence is meager to nonexistent for a link between impact and any of the other major extinctions. In considering the possible role of impacts in mass extinctions through time, I found it useful to compile the evidence of which I am aware (Table 1). For this compilation I considered eight events—the original five major extinctions, the recently added CW event, and also the minor extinction pulses at the Jurassic-Cretaceous boundary and in the late Eocene, which I included because there is substantial evidence for impact at those times. Following McGhee (1996), I expanded the FF boundary event to include the entire Late Devonian, because of substantial evidence of impacts in that ~16 Myr interval, although not necessarily precisely at the FF extinction.

Previous tables of this type were published by Rampino *et al.* (1997) and Powell (1998, p. 187). I would be surprised if Table 1 is complete, and would be grateful to be made aware of items that are missing. The lines of stratigraphic evidence useful for detecting impact are discussed in detail by Montanari and Koeberl (2000).

**EVALUATING THE EVIDENCE**

In preparing or using a compilation like Table 1, one faces the problem of evaluating the reliability of the evidence listed. This is difficult because different lines of evidence and their interpretations have followed very different historical trajectories in terms of the interest and follow-up work they have generated. Some have been extensively tested in multiple studies, such as iridium, spherules, and shocked quartz—the original big three of the KT boundary. Others are based on a single study, as in the case of chondritic Cr isotopic values or nanophase iron-rich material. When tested, some evidence holds up, some evidence is shown to be wrong, and other evidence has been ignored. At one point we thought that blind testing would be the best way to generate reliable evidence and interpretations. Blind testing did apparently give satisfactory results when applied to the question whether an iridium anomaly occurs at one or at more one horizon in the Italian Scaglia rossa limestone across the interval containing the KT boundary, although only a single brief abstract was published, giving no details (Ginsburg *et al.*, 1994). Blind testing was less satisfactory when used to test whether the KT foraminiferal extinction at El Kef, in Tunisia, was synchronous among different species, because even the results of the blind test were interpreted in conflicting ways (Canudo, 1997; Ginsburg, 1997a–c; Keller, 1997; Kouwenhoven, 1997; Lipps, 1997; Masters, 1997; Olsson, 1997; Orue-Etxebarria, 1997; Smit and Nederbragt, 1997; Aubry, 1999).

The degree of scrutiny given to any kind of evidence varies with the time it is reported, because the weight of opinion of the scientific community is evolving. As a result, the early lines of evidence for the KT impact—the big three mentioned above—were exhaustively tested and challenged, and so were the interpretations placed on them, because in the early 1980s, catastrophe was dimly regarded by most Earth scientists. Today, in a climate where catastrophes are seen as rare but inevitable events, evidence for such events is less threatening and therefore less challenged.

Additionally, in the field of impacts and extinctions, new data are less likely to be tested because no stable source of funding has been developed for workers interested in these matters. People found ways to test critical evidence when the field was new, but that is less true today.

Considering the variability in the histories of different lines of evidence, I do not see a practical way to assign reliabilities to them in a compilation like Table 1. Any such assignment would be subjective, reflecting the experience and viewpoint of the compiler. Even if the evaluation were performed by a panel of experts, the
judgment would reflect who was on the panel. My own judgments are reflected in what was included and what was omitted, in some cases after careful consideration of reviewers’ comments.

### Table 1. Evidence for Impact at Times of Mass Extinctions

<table>
<thead>
<tr>
<th>Source</th>
<th>Evidence</th>
<th>Date</th>
<th>First (?) reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Late Eocene</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Target</td>
<td>Spherules</td>
<td>1973</td>
<td>Glass et al. (1973)</td>
</tr>
<tr>
<td>Target</td>
<td>Shocked quartz</td>
<td>1993</td>
<td>Glass and Wu (1993)</td>
</tr>
<tr>
<td>Target</td>
<td>Coesite</td>
<td>1993</td>
<td>Glass and Wu (1993)</td>
</tr>
<tr>
<td>Target</td>
<td>Chesapeake crater</td>
<td>1996</td>
<td>Poag (1996)</td>
</tr>
<tr>
<td>Target</td>
<td>Popigai crater</td>
<td>1997</td>
<td>Bottomley et al. (1997)</td>
</tr>
<tr>
<td>Bolide</td>
<td>$^3$He anomaly</td>
<td>1998</td>
<td>Farley et al. (1998)</td>
</tr>
<tr>
<td>Bolide</td>
<td>Ni-rich spinels</td>
<td>1998</td>
<td>Pierrard et al. (1998)</td>
</tr>
<tr>
<td>Target</td>
<td>Shocked zircon</td>
<td>2001</td>
<td>Glass and Liu (2001)</td>
</tr>
<tr>
<td><strong>Cretaceous-Tertiary</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolide</td>
<td>Iridium in nonmarine sediments</td>
<td>1981</td>
<td>Orth et al. (1981)</td>
</tr>
<tr>
<td>Bolide</td>
<td>Os isotopic ratios</td>
<td>1983</td>
<td>Luck and Turekian (1983)</td>
</tr>
<tr>
<td>Bolide</td>
<td>Magnetic spherules</td>
<td>1983</td>
<td>Montanari et al. (1983)</td>
</tr>
<tr>
<td>Target</td>
<td>Shocked quartz</td>
<td>1984</td>
<td>Bohor et al. (1984)</td>
</tr>
<tr>
<td>Target</td>
<td>Shocked zircon</td>
<td>1990</td>
<td>Bohor et al. (1990)</td>
</tr>
<tr>
<td>Target</td>
<td>Spherules—microtektites</td>
<td>1990</td>
<td>Hildebrand and Boynton (1990), Izett (1991), Sigurdsson et al. (1991)</td>
</tr>
<tr>
<td>Target</td>
<td>Chicxulub Crater</td>
<td>1991</td>
<td>Hildebrand et al. (1991)</td>
</tr>
<tr>
<td>Bolide</td>
<td>Irregular Ir-rich particles</td>
<td>1993</td>
<td>Robin et al. (1993)</td>
</tr>
<tr>
<td>?</td>
<td>Diamonds in proximal ejecta</td>
<td>1997</td>
<td>Hough et al. (1997)</td>
</tr>
<tr>
<td>Bolide</td>
<td>Fullerenes with $^3$He</td>
<td>2000</td>
<td>Becker et al. (2000)</td>
</tr>
<tr>
<td>Bolide</td>
<td>Nanophase Fe-rich material</td>
<td>2001</td>
<td>Wdowiak et al. (2001)</td>
</tr>
<tr>
<td><strong>Jurassic-Cretaceous</strong></td>
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<td></td>
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<td>Target</td>
<td>Gosses Bluff Crater</td>
<td>1987</td>
<td>Milton and Sutter (1987)</td>
</tr>
<tr>
<td>Target</td>
<td>Mjølnir Crater</td>
<td>1996</td>
<td>Dypvik et al. (1996)</td>
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<td>Target</td>
<td>Morokweng Crater</td>
<td>1997</td>
<td>Koebel et al. (1997)</td>
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<td><strong>Triassic-Jurassic</strong></td>
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<tr>
<td>Target</td>
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<td>1992</td>
<td>Bice et al. (1992)</td>
</tr>
<tr>
<td><strong>Permian-Triassic</strong></td>
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<tr>
<td>Bolide</td>
<td>Fullerenes with $^3$He</td>
<td>2001</td>
<td>Becker et al. (2001)</td>
</tr>
<tr>
<td>Bolide</td>
<td>Nanophase Fe-rich material</td>
<td>2001</td>
<td>Verma et al. (2001)</td>
</tr>
<tr>
<td><strong>Capitanian-Wuchiapingian</strong></td>
<td></td>
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<tr>
<td>Late Devonian</td>
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<td></td>
<td></td>
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<tr>
<td>Target</td>
<td>Siljan Crater</td>
<td>1990</td>
<td>Bottomley et al. (1978, recalculated 1990)</td>
</tr>
<tr>
<td>Bolide</td>
<td>Iridium</td>
<td>1993</td>
<td>Nicoll and Playford (1993)</td>
</tr>
<tr>
<td>Target</td>
<td>Alamo shocked quartz</td>
<td>1995</td>
<td>Leroux et al. (1995)</td>
</tr>
<tr>
<td>Target</td>
<td>Woodleigh Crater</td>
<td>2001</td>
<td>Uysal et al. (2001)</td>
</tr>
<tr>
<td><strong>Ordovician-Silurian</strong></td>
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<td></td>
</tr>
<tr>
<td>Late Devonian</td>
<td>No published evidence for impact</td>
<td></td>
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</tbody>
</table>

PGE, platinum group element.

### Asymmetries Between Impacts and Flood Basalts

Choosing between impact and flood basalts as the cause of any extinction in particular, or of ex-
tinctions in general, is inherently difficult because of the remarkable differences in the characteristics of the two phenomena and the way they are recorded.

Areas covered

Flood-basalt provinces are said typically to cover areas of \( \sim 10^6 \) km\(^2\). The Siberian Traps are generally considered to be the largest such province on continental crust, with an area of \( \sim 1.5 \times 10^6 \) km\(^2\), but much of this area exposes pyroclastic volcanics and intrusives, with the actual basalts covering only \( \sim 3.4 \times 10^5 \) km\(^2\), although of course the pre-erosion area of basalts may have been much greater (Zolotukhin and Al’Mukhamedov, 1988; Wignall, 2001).

By contrast, the Chicxulub Crater, with a diameter of 180 km\(^2\), covers an area of \( \sim 25,000 \) km\(^2\). Increasing this by a factor of 3 or 4 to include the area covered by a thick ejecta blanket gives an area of \( \sim 10^5 \) km\(^2\), an order of magnitude lower than the typical flood basalt. Although distal impact ejecta may cover an area larger than that of a flood-basalt province, distal ejecta are thinner and less distinctive than even a single flood-basalt flow. Clearly there will be a bias in preservation and recognition, with flood basalts more likely to be found than even the largest terrestrial craters.

Distal proxies

Most of the lines of evidence for impact in Table 1 are distal proxies recovered from the sedimentary record at long distances from the corresponding impact crater. Global or near-global distribution of proxies occurs in impact events because the fireball is large compared with the thickness of the atmosphere and it launches ejecta on ballistic trajectories. Although long-distance trajectories are complicated because of the Earth’s rotation (Alvarez, 1996), most or all of the Earth can be reached. In the case of flood basalts, it seems unlikely that volcanic material will leave the atmosphere. Only gases and the finest aerosols will be able to travel long distances. It is not obvious that gases and aerosols would leave a record identifiable in the sedimentary rocks.

Even if recognizable distal proxies for flood basalt eruptions are predicted or discovered, they will be spread out over a stratigraphic interval on the order of 1 million years, which is the usually quoted duration of a flood-basalt episode. Depending on the residence time of the hypothetical proxy in the atmosphere and ocean, it may be deposited in many layers, corresponding to the individual eruptions during the flood-basalt episode, and each containing a small fraction of the total amount of the proxy, or it may be diluted in a thick interval of sedimentary rocks. In either case it will be difficult to find. These considerations indicate that it will be hard to use remote proxies to falsify the hypothesis that flood basalts are a general cause of mass extinctions.

Duration of the event

As a third asymmetry, impact events are geologically instantaneous, with most proxies deposited in days to months, and even the most persistent environmental effects, notably atmospheric CO\(_2\), probably cleaned up in a few thousand years. In contrast, radiometric dating shows that flood-basalt events continue with many eruptions over a million years or so. It is thus easier to falsify an impact–extinction connection than a proposed connection between a flood-basalt province and an extinction.

For example, at Gubbio, in Italy, the impact proxies (iridium anomaly and spherules) reside in a 1-cm-thick clay layer precisely separating Cretaceous and Paleocene faunas. The clay is within a 6-m zone representing the 29R reversed polarity zone (Lowrie and Alvarez, 1977), which lasted \( \sim 0.58 \) Myr years (Harland et al., 1990, p. 157). The impact and the extinction are therefore synchronous to better than 100,000 years, and probably better than 10,000 years. If the two were asynchronous by \( >100,000 \) years, this would be easily detectable in the stratigraphic record, and a proposed connection would be falsified.

As an example of the case for flood basalts, Deccan volcanism records an entire reversed magnetic polarity zone (Courtillot et al., 1988), thought to be the 29R zone (Courtillot, 1995, p. 102), and parts of the preceding and subsequent normal polarity zones. Deccan volcanism therefore lasted \( >0.5 \) million years, and it is harder to falsify a proposed connection with the nearly instantaneous KT extinction, which happened during that long time interval.

In his abstract, Wignall (2001) states, “Curiously, the onset of eruptions slightly post-dates the main phase of extinctions in these examples [Emeishan, Siberian, CAMP, and Karoo traps].” This would seem to argue against flood volcanism as a cause of extinction, but a careful reading of the paper suggests that these age differences are beyond the resolution of the data and that this
is not a strong argument against a link between flood basalts and mass extinctions. Probably a stronger argument against a flood basalt–extinction link is the fact that other large flood-basalt provinces (Paraná–Etendeka, Ethiopia) are not associated with mass extinctions.

**Killing mechanisms**

In a further asymmetry, it is much easier to understand how mass extinctions might be caused by impacts than by flood basalts. Not only are globally distributed proxies more recognizable for impacts than for flood basalts, but numerous global killing mechanisms have been suggested for impacts. In the KT case, these include infrared heating from ballistic ejecta re-entering the atmosphere and the continent-scale wildfires that would result (Melosh et al., 1990), darkness and cold from globally distributed dust (Alvarez et al., 1980) [although this has recently been challenged by Pope (2002)], sulfuric and nitric acid rain (Lewis et al., 1982), and sulfate aerosols (Kring, 2000), and probably greenhouse heating from both water vapor and carbon dioxide.

In the case of flood basalts, it has not been clear how they could cause mass extinctions, which must of necessity be global. In his review, Wignall (2001, pp. 2–5) finds “little evidence for a link between individual volcanic eruptions and climate change, and no evidence at all for a link with extinctions,” at least for explosive eruptions and for the largest observed quiet basaltic eruption (Laki, in Iceland, in 1783–1784). He notes, however, that ancient continental flood-basalt provinces have involved fissure eruptions orders of magnitude larger than Laki. He suggests that fire fountaining during these events may be able to inject large amounts of volcanic gases into the stratosphere, where they could affect global climate. Large historical eruptions that produced climatic disturbances, notably from sulfuric acid-aerosol “dry fogs,” from which the effects of much larger flood-basalt eruptions would have to be scaled up, have been described by Stothers (1999, 2000), and the climatic effects of large fissure eruptions on Iceland, the closest actualistic analogues to flood basalts, were documented by Stothers (1996, 1998).

**CONCLUSIONS**

Unfortunately the only general conclusion emerging from this review is that we cannot yet draw conclusions about a general cause of mass extinctions. The cases for impact and flood-basalt eruptions as general causes are completely different.

Impact as a general cause is not supported by evidence for impact at multiple extinction horizons. Of course, absence of evidence does not constitute evidence of absence, and it may be that there have been several extinction-causing impacts, with the KT event unique in its abundant preservation of impact proxies. One may conclude that impact as a general cause of extinctions is not supported by evidence, but has not been falsified.

Flood-basalt volcanism as a general cause is supported by time correlations of four flood basalt–extinction pairs, although there are other flood-basalt provinces with no corresponding mass extinction. And even if each flood basalt were followed by an extinction, one could not reliably infer a causal relation.

A different relationship might be controlling the correlation. Perhaps both flood basalt and extinction are the results of some other cause, such as impact. Boslough et al. (1996) suggested that axial focusing of impact-generated seismic waves could trigger a mantle plume and thus flood-basalt volcanism antipodal to an impact site; unfortunately, in the only testable case, the Deccan Traps were ~50° away from the point antipodal to the Chicxulub Crater at the time of the KT extinction. No volcanism was triggered at the Chicxulub impact site; however, the antipodal point has been subducted, so the Boslough hypothesis is untestable in this case. Muller (2002) suggests another possible relationship, in which impacts might trigger avalanches at the core–mantle boundary, which in turn could trigger plume rise and flood-basalt volcanism. One may conclude that the hypothesis that flood basalts are the general cause of mass extinctions is supported by evidence from timing, but is not susceptible to falsification.

What is necessary in order to resolve this question? A critical need is to identify a remote proxy for recognizing flood-basalt eruptions in the stratigraphic record. Ideally this would record each major basalt flow. Precise information on the rapidity of extinction events and their exact placement in the stratigraphic record is vital. We also need one or more credible mechanisms by which flood basalts could cause global extinctions. We need to identify and focus on impact proxies that will be produced in an oceanic impact, because target-sourced proxies like spherules and shocked
quartz probably will not be produced. Finally, thought must be given to possible ways in which both flood basalts and extinctions might be caused by impact.

ACKNOWLEDGMENTS

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ABBREVIATIONS

CAMP, Central Atlantic Magmatic Province; CW, Capitanian-Wuchiapingian; FF, Frasnian-Fammenian; KT, Cretaceous-Tertiary; OS, Ordovician-Silurian; PT, Permian-Triassic; TJ, Triassic-Jurassic.

REFERENCES


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