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SPOTLIGHT

IMPACTS AND MASS EXTINCTIONS REVISITED

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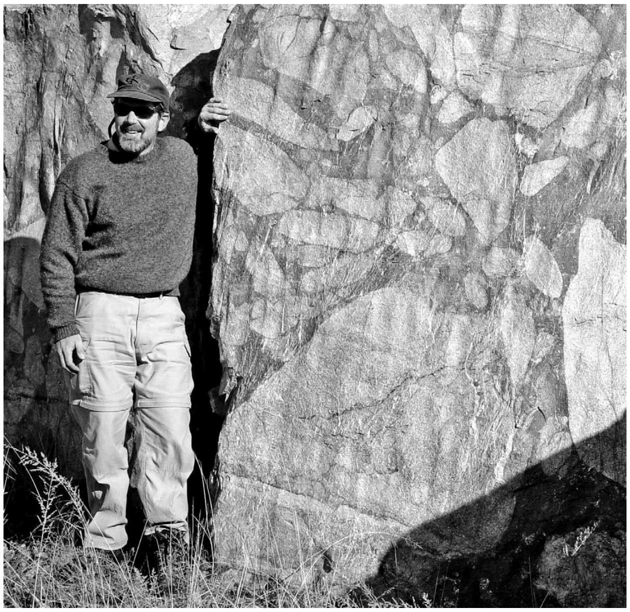
On several occasions at impact geology- and paleontology-related meetings during the past 10 years, I have heard the statement from colleagues that major extinctions must be linked to large asteroid or comet impact events because "what else could it be?" (i.e., what other known mechanisms, terrestrial or extraterrestrial, could drive the geologically rapid loss of a majority of Earth's species?) Although I am strongly pro-impact in my view of Earth history, I think that it is time to reappraise our state of knowledge within impact geology and mass-extinction research, and to examine the widely postulated link between impacts and mass extinctions more critically. It has been over 25 years since the landmark study of Alvarez et al. (1980) launched the global-scale search by the geological and paleontological communities for quantitative, testable evidence tying impact to extinction. Where then do we stand today? In this SPOTLIGHT, I highlight some recent advances in impact geology that have direct bearing on our ability to recognize the signature of ancient impact events and on our ability to link these events to mass killings.

The continuing challenge (and frustration!) facing any hypothesized link between impact and extinction is well illustrated in Figure 1. Major biotope events documented in the fossil record may have been driven by a number of very different, potentially interacting causes, both telluric (terrestrial) and cosmic (extraterrestrial) in ultimate origin. These could lead via very different pathways to results that are, at least superficially, very similar. Of the proposed cosmic mechanisms responsible potentially for driving biotic crises, large-body hypervelocity impact remains the most important and the most readily testable in the geological record.

An important outcome of research by impact and planetary geologists is the realization that impact cratering is a continuing, active process that has affected the long-term development of many Earth systems strongly, including the biological (e.g., French, 2004). Increasing interest by professional and amateur researchers, expanding subsurface exploration for hydrocarbon resources, ongoing mapping of the ocean floor, advances in satellite imaging, and the development of automated, digital crater-detection programs have greatly increased the number of previously unrecognized, potential impact sites. Comparison of published Earth crater counts clearly demonstrates the growing number of possible identified impact structures—compare early crater tabulations, for example, by Dietz (1961; 14 structures identified) with such recent, continually updated, web-based impact databases as those maintained by the Planetary and Space Science Centre, University of New Brunswick (<http://www.unb.ca/passc/ImpactDatabase/index.html>; 174 confirmed structures now identified), and by D. Rajmon and the Impact Field Studies Group, University of Tennessee (see the SEIS, Suspected Earth Impact Sites, links at <http://web.eps.utk.edu/ifsg.htm>). The SEIS database now lists over 500 confirmed, probable, and possible impact sites. With continuing interest in impact events, this number will continue to grow.

With regard to driving mass-extinction events, of course the question is not only one of "how many craters?" but also of "how large are they?" Impact-kill curves (Raup, 1992; Jansa, 1993; Poag, 1997), which postulate a relationship between crater diameter and percent biotic extinction, suggest that mass extinctions (i.e., the rapid loss of ~50% or more species globally) require a crater size of ~150 km or more in diameter. This threshold-size requirement, which may in fact be an underestimate, limits greatly the list of known potential mass-extinction-producing impacts. In light of recently developed, high-resolution tools for detecting the distal geological record of impacts, discussed below, an additional question might be "how difficult is it to hide all the evidence of an impact large enough to cause a mass extinction?" Or, less facetiously, given advances in our ability to identify impact deposits and even minute impact-related geochemical anomalies, should not links between impact events and mass extinctions now be easier to demonstrate?

Multiple sub-critical impacts have been proposed to have cumulative environmental effects capable of driving mass extinction, although the timing of the impacts and of the subsequent extinction peak may be offset significantly (McGhee, 2001). The closely timed late Eocene Chesapeake



Jared Morrow (doing his best "Vanna White" impression beside spectacular pseudotachylitic melt breccia of the Vredefort impact structure, South Africa) recently joined the faculty in the Department of Geological Sciences, San Diego State University. This follows eight years of dodging cow pies on the High Plains of northeastern Colorado, where he served as an assistant and associate professor of geology in the Department of Earth Sciences, University of Northern Colorado. His career includes a Geology B.A. from Humboldt State University (California), a stint as a mudlogging geologist, work as a USGS Physical Science Technician, and a Geology M.S. from Washington State University. Surviving on Bill Evans' jazz, cheap scotch, and sketchy karma at the University of Colorado-Boulder, he completed his doctoral and post-doctoral work in 1998 on the event stratigraphy, sedimentology, and conodont biostratigraphy of the F-F mass extinction interval, central Great Basin, and Western Europe. Since that time, he has contributed to several impact projects, including collaborative work on the Alamo event, Nevada and Utah; the Peerless structure, Montana; the Wetumpka crater, Alabama; the Bosumtwi crater, Africa; and the Chesapeake Bay crater, Virginia. Photo credit: C. Koeberl, University of Vienna.

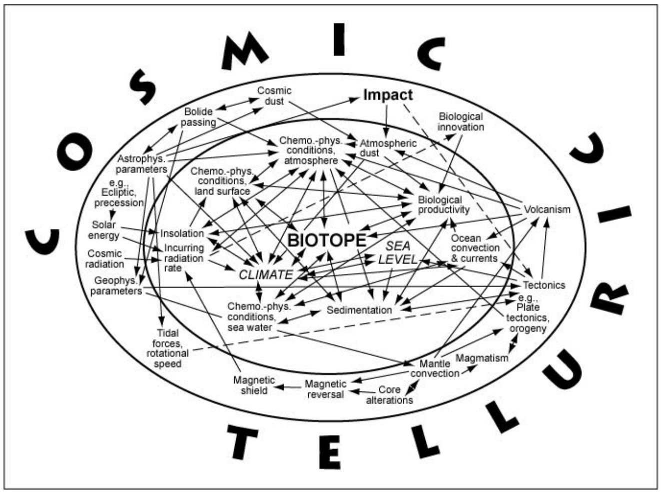


FIGURE 1—Flow chart showing the possible driving mechanisms and complex interactions that could lead ultimately to a global bioevent (after Walliser, 1996).

and Popigai impacts preceded significant biotic turnover at the Eocene-Oligocene boundary by ~1–2 m.y. (Poag, 1997). Similarly, multiple Late Devonian impacts preceded the stepped mid-Late Devonian (F-F) mass extinction by ~0–6 m.y. (McGhee, 2001; Sandberg et al., 2002; Reimold et al., 2005). If, however, multiple sub-critical impacts are implicated as a killing mechanism, a model must be developed that allows the impact-related environmental effects not only to be cumulative but also to be either very long lived or capable of working in concert with other, presumably telluric, causes.

In order to play the impact-extinction game, however, the research focus must switch necessarily from the craters themselves to the regional-to-global effects of large impact events and their potential causal links with rapid ecosystem collapse. Extra-crater impact evidence is both proximal (i.e., $\leq$5 crater radii from the crater rim) and distal (i.e., $>$5 crater radii from the rim), and can include seismic, thermal, and acoustic effects; anomalous monomict and polymict lithic- and melt-rich breccias; distal, fine-grained lithic- and melt-rich ejecta; and, in the case of marine impacts, tsunami deposits (French, 1998; Koeberl, 2001). A major challenge of impact studies is correlating distal evidence of an event to its source crater, which often may be undiscovered or may have been obscured or destroyed by active Earth processes. Even where the record is well preserved and extensive data are available, as for the Cretaceous-Tertiary (K-T, now K-P) boundary Chicxulub crater and its associated deposits, confidently tying distal effects to a specific crater requires a sophisticated integration of high-resolution stratigraphic, biostratigraphic, radiometric, petrographic, and geochemical fingerprinting techniques (Koeberl, 2001; Kyte, 2002). A further complication is accurately tying radiometrically dated impact craters and ejecta with biochronologic units (Koeberl, 2001), which are usually more closely linked to the mass-extinction record itself. Constant refinement and realignment of numerical timescale and biozone boundaries therefore represent an ongoing challenge.

Current methods of verifying an impact origin for distal deposits are focused on (a) recognizing the presence of shock-metamorphosed or -melted target materials, based on such diagnostic criteria as microscopic planar deformation features (PDFs) in mineral grains, anomalous high-pressure mineral phases, diaplectic mineral glasses, and rock and mineral melts (French, 1998); and (b) identifying geochemically the presence of trace amounts of meteoritic material within the deposits (Koeberl, 2001). Important geochemical evidence of a meteoritic component comprises unusual concentrations or ratios of platinum group and other siderophile elements, including the oft-sought iridium (Ir), and diagnostic isotopic tracers, such as ^{187}Re/^{187}Os, ^{187}Os/^{186}Os, ^{53}Cr/^{52}Cr, and ^{3}He/^{4}He (Koeberl, 2001; Kyte, 2002).

Recent work reexamining an Ir anomaly and purported shocked quartz at the Permian-Triassic boundary (Koeberl et al., 2004, and Langenhorst et al., 2005, respectively) underscores the responsibility on impact and extinction researchers to apply multiple, quantitative analytical techniques rigorously before assigning an impact cause to a mass-extinction event. The outcome of recent multi-disciplinary work is that not all planar microstructures in quartz are shock-generated PDFs and not all Ir anomalies are impact produced. An implication of this research is that small-to-moderate (i.e., $<$1-part-per-billion-range) Ir anomalies identified previously at biotic crisis intervals need to be reexamined, in order to confirm a meteoritic origin and to eliminate such potential non-impact sources as biologic concentration (Nicoll and Playford, 1993), marine anoxia (Koeberl et al., 2004), or volcanism (Koeberl, 1989).

A caveat to this discussion, however, is that any given impact event may not display or preserve all of the possible diagnostic sedimentologic, petrographic, and geochemical criteria. The resulting final crater and extra-crater deposits are a complex function of target lithology, target rheology, target volatile content, impactor type (asteroid or comet), paleogeographic setting of impact (marine or continental), and paleolatitude of impact (affecting ejecta distribution). Therefore, a quantitative, multi-proxy approach is absolutely critical, especially where possible distal impact deposits are not yet tied to a potential source crater.

With respect to impact and mass-extinction events, then, our testable evidence continues to grow at a rapid rate. We have several new analytical tools to identify both the direct and indirect evidence of ancient impact events. During the past 25 years, the quantity and quality of high-resolution paleontological data across major biotic crisis intervals have similarly increased. Recently developed online databases, such as the Paleobiology Database (http://paleodb.org/cgi-bin/bridge.pl) and CHRONOS (http://chronos.org), promise to provide a dynamic new integrative tool for assessing further the timing, mode, and magnitude of biotic loss at mass-extinction episodes. Although the imperfection and bias of the geological and paleontological records will continue to hamper impact and extinction studies, we should now have a sufficiently robust dataset to verify episodes of catastrophic biotic loss and to ask, "where are the killer impacts?"

Despite intense sampling across the big five mass-extinction intervals since the work of the Alvarez et al. team, the K-P boundary remains the best-documented example of an impact-related event; it may be unique because of the well-preserved crater, proximal deposits, and global ejecta layer (a function partly of preserved oceanic crust of this age). Some K-P boundary workers have reported evidence of multiple impacts across this interval (e.g., Keller et al., 2003), but all workers acknowledge at least one large impact at this boundary, which is the most critical point when trying to implicate impact with the mass extinction.

Results from the other of the big five intervals are less conclusive. Data proving a large impact event at the Permian-Triassic boundary remain equivocal (Koeberl et al., 2004). Although a recent hypothesis has postulated a link between gamma-ray bursts and the latest Ordovician mass extinction (Melott et al., 2004), strong evidence for large-body impact at this interval is lacking. Recent refinement of the radiometric age of the mid-Late Devonian Siljan crater, Sweden, and recalibration of the Devonian numerical timescale have placed the timing of this impact, within error estimates, at the F-F boundary (Reimold et al., 2005). The Siljan event, however, was probably too small to drive the extinction by itself. The other pre-F-F Late Devonian impacts were sub-critical and occurred well before the most severe mass-extinction steps. Although several studies have discussed the potential that the end-Triassic mass extinction was coincident with an impact event (e.g., Olsen et al., 2002), the temporal and geological evidence linking impact and extinction during this crisis are less well proven than for the K-P. Documented Late Triassic impact structures (Spray et al., 1998) predate the Triassic-Jurassic boundary by nearly 14 m.y., and thus were unlikely direct mechanisms of the end-Triassic extinction.

So, where then does this leave us? Judging by the K-P boundary (a sample size of one!), it would seem that the impact(s) required to cause a mass extinction should leave a widespread, probably global, and geologically durable record, even if the craters have been destroyed subsequently by Earth processes. We now have the high-resolution datasets and analytical tools to detect such large impact events and to correlate these events more confidently with the fossil record. We should soon be able to answer the question ''where are the killer impacts?'' And sadly for a pro-impact geologist like myself, the perpetrators may be found elsewhere on the biotope-crisis flow chart (Fig. 1), perhaps within the telluric records of volcanism or of less fully known mantle convection. At the very least, however, we now have the data and techniques to examine more critically the statement ''what else could it be?'' The challenge and responsibility now lay on the impact geological and paleontological communities to work collaboratively in order to apply rigorously these new tools.

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