

The Influence of Large Bolide Impacts on Earth's Carbon Cycle

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Human society's rapid release of vast quantities of CO₂ into the atmosphere is a significant planetary experiment. An obvious natural process capable of similar emissions over geologically short time spans are very large bolide impacts. When striking a carbon-rich target, bolides significantly, and potentially catastrophically, disrupt the global biogeochemical carbon cycle. Independent factors, such as sulfur-rich targets, redox state of the oceans or encountering ecosystems already close to a tipping point, dictated the magnitude of further consequences and determined which large bolide strikes shaped Earth's evolution. On the early Earth, where carbon-rich sedimentary targets were rare, impacts may not have been purely destructive. Instead, enclosed subaqueous impact structures may have contributed to initiating Earth's unique carbon cycle.

KEYWORDS: impact target, volatilization, spherule beds, tipping points, ocean redox

INTRODUCTION

Large bolide impact events have become rare. At most, there is one strike of one ~10 km object every 100–200 million years (My). But the rich history of former bombardment is evident on the surfaces of inner solar system bodies, as well as from the few preserved impact features on Earth itself (e.g., Reimold and Jourdan 2012). Impact basins more than 1,000 km across exist on our planetary neighbours and they are pockmarked with thousands of smaller impact features. Counting crater numbers and measuring the sizes of craters on images of the Moon's surface qualitatively shows that most of the very large basins formed early in the history of the solar system. Dates for lunar samples constrain the bulk of the bombardment to have occurred within the first ~700 My since planet formation. Importantly, however, significant events capable of producing basins hundreds of kilometres in diameter also happened in more recent history. It is instructive to study how these could have disrupted the complex interplay between biology and geology on Earth; that is, how they have affected the global biogeochemical carbon cycle.

The Earth's geological history is subdivided into eons, eras and periods (Fig. 1). For the older eras, these subdivisions were defined with the appearance or disappearance of dominant rock types, whereas most boundaries of the

younger eras and periods coincide with the rapid disappearance of organisms (mass extinctions). Many scientists suggest that the Earth has recently transitioned into a new period – the provisionally termed “Anthropocene” – this is defined to reflect the planet-wide effects of human activity. The Anthropocene could be described as a gigantic combustion experiment in which reduced, energy-rich forms of C (e.g., coal, oil, gas, wood) are oxidized to CO₂, with additional significant atmospheric emissions from industrial and land-use activity. The cumulative atmospheric CO₂ release since AD 1750 is ~2,000 Gt (Boden et al. 2009). For comparison, the

bolide strike that formed the ~66 Ma Chicxulub structure (Mexico) released between 425 Gt and 1,400 Gt of CO₂ (Artemieva et al. 2017; Brugger et al. 2017). Thus, some large bolide impacts are comparable to the Anthropocene effect in terms of the rapid disruption of the carbon cycle and the potential for exceeding the currently unknown critical degree of perturbation (e.g., Rothman 2017). However, during the most intense bombardment period on the early Earth, the surface was poor in the C- and S-rich sediments that exert the greatest control over climate perturbation. Time, therefore, provides a natural narrative for a review of environmental consequences.

IMPACTS ON THE VERY EARLY EARTH

The Hadean Eon (4,567 Ma to ~3,850 Ma) is the oldest eon of Earth's history, and it witnessed by far the largest number of impacts. Unfortunately, the Hadean geological record is very sparse and significant uncertainty exists about Earth's evolution during that time. Nevertheless, three key questions are of great scientific importance because of their enduring legacy for the remainder of Earth history. They all relate to the Hadean impact history (e.g., Grieve and Stöffler 2012):

1. Did the Hadean bombardment deliver volatile elements, including water and carbon, to the early Earth?
2. What happened to the Earth's vanished primordial crust?
3. Was life on Earth already established during the Hadean?

The delivery of extraterrestrial matter to Earth happens with two dominant size classes of objects: the tiniest, and the largest. The fully formed Earth was struck by a few hundred bolides capable of causing very large (>100 km) impact basins (Bottke et al. 2012), and these objects contained at least one-third of the delivered extraterrestrial

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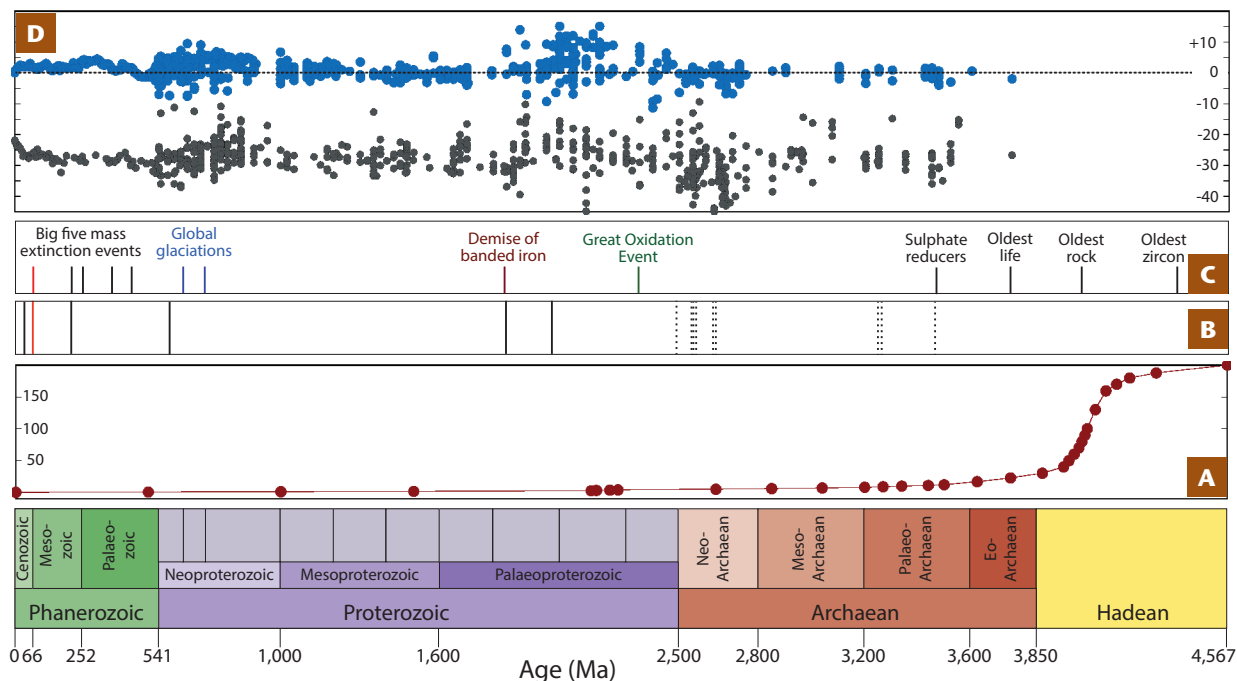


FIGURE 1 (BOTTOM CHART) Timeline of significant geologic events relative to geological age, subdivided into the four, colour-coded, geological eons (Hadean, Archaean, Proterozoic, Phanerozoic). The Hadean–Archaean boundary is after Kamber (2015). The eons are subdivided into the geologic eras; the boundaries of the Proterozoic periods are shown but not named. (A) The cumulative age-distribution of bolides capable of creating basin-sized impact structures on Earth (number as y-axis). AFTER BOTTKÉ ET AL. (2012). (B) The ages of the six largest known terrestrial impact events (as solid lines during the Proterozoic and Phanerozoic) and

the most prominent spherule layers (as broken lines, all during the Archaean). AFTER JOHNSON AND MELOSH (2012). The Chicxulub (Mexico) impact is shown in red. (C) A summary of key events and preserved pieces of evidence relevant to planetary evolution. The K–Pg [formerly the K–T] extinction event shown as a red vertical bar. (D) Global data compilation of the carbon isotope compositions (δ¹³C as y-axis) of carbonate (blue symbols) and organic carbon (dark grey symbols). DATA FROM KRISSENSSEN-TOTTON ET AL. (2015) AND SCHIDLÓWSKI ET AL. (1973).

matter. At the other end of the spectrum, cosmic dust, having particle diameters in the micrometre range, constitutes the second significant source of extraterrestrial matter (Peucker-Ehrenbrink et al. 2016). Of the two types of impactors – comets and asteroids – comets are predominantly composed of volatile species (O, C, H, N), whereas asteroids include undifferentiated chondritic bodies that also contain ~1.1 wt% H and ~1.8 wt% C (e.g., Alexander et al. 2012), with organic molecules. Although intuitively, this suggests that the delivery of such matter to Earth during the Hadean might have contributed to the build-up of the hydrosphere and to the *surficial* C reservoir, this simple logic is complicated by impact physics.

Comparing the delivery of extraterrestrial elements of a refractory nature (i.e., with a high boiling temperature) to those of a volatile character (low boiling temperature) shows that most of the volatile cargo would be lost from cosmic dust upon its atmospheric entry (Peucker-Ehrenbrink et al. 2016), except for particles <35 μm which experience limited frictional heating. Impacts of larger bolides at velocities in excess of ~15 km/s cause at least partial vapourization of the target and intense heating to >10,000 K of the vapourized material (e.g., Collins et al. 2005), and this leads to the formation of a silicate vapour plume. The behaviour of the various chemical elements in these plumes, particularly atmospheric escape versus condensation and fallback to the Earth, is currently not fully understood. The isotopic systematics of light elements and noble gases suggest that late addition to the Earth from comets is unlikely to have been volumetrically important for water, nitrogen and carbon (Alexander et al. 2012). Current evidence favours an origin of the terrestrial volatiles by early capture during planetary accretion rather than by late addition during very large impact events.

Regardless of the origin of volatiles, the rate at which the lunar surface was bombarded (and, by analogy, the Earth)

can be reconstructed by combining crater density statistics with the known ages of rocks from the Moon's surface (e.g., Reimold and Jourdan 2012). The largest uncertainty in this flux estimate arises from the paucity of samples returned from the older, more heavily cratered dark side of the Moon and the few direct dates for large lunar impact basins (e.g., Bottke and Norman 2017). There are two end-member models for the bombardment flux: one that envisages a spike in very large impacts between 3,850 Ma and 4,200 Ma (the late heavy bombardment, or LHB) versus one that favours an exponentially decaying flux (the “accretion tail scenario” of Morbidelli et al. 2018). With currently available data, modelling cannot unequivocally rule out either scenario. One of the strongest pieces of evidence in favour of the LHB remains the U/Pb age line of lunar highland samples (Tera et al. 1974) that was originally used to advance the concept of a late bombardment. This line is interpreted to date the timing of volatile element loss and homogenization. The age conspicuously coincides with the more widespread preservation of terrestrial rocks, i.e., the Archaean–Hadean boundary (FIG. 1). If future lunar data confirm the existence and timing of the LHB, one of the most significant environmental consequences of very large bolide impacts on Earth could have been the destruction of the protocrust. On Mars and Mercury, the ancient protocrusts persisted, despite bombardment, but the LHB on Earth may have been effective at crust destruction if the crust–mantle system had reached a vulnerable state, due, for example, to build-up of internal heat (e.g., Kamber 2015).

ARCHAEOAN IMPACTS AND THE EARLIEST CARBON CYCLE

With no supracrustal rocks of Hadean age preserved, the question of putative Hadean life and its effects on the carbon cycle cannot be studied directly. By contrast, the

Archaean sedimentary record does contain samples with remains of organic (reduced) carbon, as well as carbonate, and there is clear evidence that the Archaean Earth was struck by very large bolides. No unequivocal Archaean impact basins have been found to date. Instead, the evidence for impacts comes from so-called spherule layers within sedimentary sequences (e.g., Simonson and Glass 2004). These tell-tale sediment layers are millimetre-to-metre thick, laterally continuous, and contain spherules of various compositions, some with evidence for quench cooling, high pressure minerals, or shock features. The first important inference drawn from their distribution in time (FIG. 1) is that the Earth continued to be bombarded with large bolides well beyond 3,850 Ma (e.g., Lowe et al. 2014) and that the Archaean witnessed more large impacts than the later eons (e.g., Bottke et al. 2012). Because many spherule beds are enriched in iron-loving (siderophile) elements, it has also been possible to incontrovertibly prove that some layers have had a contribution to their formation from a vapourized asteroid, for example via the isotope composition of Cr (e.g., Kyte et al. 2003).

A particular advantage of studying spherule beds is that they are preserved within a stratigraphic context (Simonson and Glass 2004). This provides additional sedimentological information and geochemical evidence of potential environmental disruption. Most of the well-preserved Archaean spherule beds from the Kaapvaal Craton (southern Africa) and the Pilbara Craton (western Australia) show evidence for sedimentary redistribution caused by currents and/or waves (e.g., Lowe et al. 2014). The consistent occurrence of spherules within reworked eroded local detritus rather than the pure deposits of constant thickness expected from fallout, strongly suggests that reworking was a consequence of the impact itself via tsunamis, impact-induced turbidity currents, or bottom return flows.

Johnson and Melosh (2012) concluded that most of the spherule bed-forming bolides were 20–50 km in diameter and would have excavated transient craters of up to 100 km deep and final basins reaching several hundred kilometres in diameter. To date, no such basin has actually been discovered. One interesting area of future research is the question of shock-metamorphism of the lithospheric mantle during excavation and collapse of transient cavities well below the crust–mantle boundary. In terms of environmental and carbon isotope consequences, the impact that caused the 2,629 Ma spherule layers in Western Australia and South Africa is particularly instructive because it is found within carbonate (mostly dolomite), which is conducive to chemical and isotopic analysis. According to Johnson and Melosh (2012), the corresponding impact basin would have been ~100–150 km in diameter and, thus, represent a significant event. The carbon isotope values for reduced carbon across the spherule bed do not show an incontrovertible trend, but nonetheless indicate a significant general shift towards lighter carbon from $\delta^{13}\text{C}$ of -42‰ to -48‰ (Eigenbrode and Freeman 2006). By contrast, the shallow marine carbonate $\delta^{13}\text{C}$ (δ_{carb}) values remain near 0‰ across the spherule bed, but these data were obtained at a more limited spatial resolution that may not have captured the disruption of the global biogeochemical carbon cycle. More detailed isotopic studies across spherule beds are needed to explore to what extent the balance between the buried sedimentary reduced carbon and the dissolved oceanic carbon was disrupted by these impact events.

Carbonate is a less dominant sediment type in the Archaean supracrustal rock record than in the Proterozoic and the Phanerozoic. Therefore, it is impossible to produce a continuous global carbonate carbon isotope record that would cover all the ~15 known Archaean spherule layers to test how representative the 2,629 Ma event was. Notwithstanding this limitation, it is evident from the existing global compi-

lation (FIG. 1) that the presently documented fluctuations in Archaean δ_{carb} were much less pronounced than in the Palaeoproterozoic and Neoproterozoic (e.g., Krissansen-Totton et al. 2015). Regardless of the potential of very large bolide impacts to temporarily disrupt the ancient carbon cycle, the apparent stability of the cycle itself, as well as the similarity of the predominant Archaean δ_{carb} with modern carbonate carbon, is astonishing. The oldest carbonates occur in the Isua Greenstone Belt (Southwest Greenland). They are between 3,710 Ma and 3,810 Ma and, although not universally accepted as sedimentary in origin, some appear to have yielded δ_{carb} close to the modern-day value of zero, and they have co-existing very light carbon preserved in putative biogenic graphite (Schidlowski et al. 1979). Due to the pervasive metamorphic overprint of the Isua rocks, some doubt remains as to whether the recorded carbon isotope values truly reflect the sedimentary system. Regardless, many more paired reduced carbon and δ_{carb} values have been reported for younger Archaean sedimentary rocks, leaving little doubt as to the stability of the early terrestrial carbon cycle (e.g., Krissansen-Totton et al. 2015).

PROTEROZOIC IMPACTS AND THE OCEAN–ATMOSPHERE SYSTEM

Of the six largest preserved terrestrial impact structures, three are Proterozoic in age: the 2,023 Ma Vredefort impact structure (South Africa); the 1,849 Ma Sudbury Basin (Canada) and the 580–590 Ma Acraman crater (South Australia) (FIG. 1). Due to deep erosion of the Vredefort structure and the lack of a confirmed corresponding impactite layer, it is impossible to reconstruct the environmental consequences of Earth's largest preserved bolide impact. By contrast, both the Sudbury and Acraman events preserve remnant impact structures, as well as corresponding impactite layers in the sedimentary record. These two impact events are, therefore, more conducive to studying putative global environmental consequences.

The impact layer corresponding to the Sudbury Basin is found up to 700 km away in the Fe-rich sedimentary strata of the Lake Superior region of North America (e.g., Cannon et al. 2010). The layer is a breccia containing lithic fragments (some shocked), devitrified glasses of various kinds, as well as accretionary lapilli (FIG. 2); this layer differs from the Archaean spherule beds described in the previous section. Of critical importance is that the breccia layer occurs within a Palaeoproterozoic sedimentary context (FIG. 2). The bolide is believed to have hit a foreland basin covered by relatively shallow water (e.g., Ubide et al. 2017), and the main excavated rocks were quartz-rich sandstones of the >2,200 Ma Huronian Supergroup and Archaean basement. These contained very little carbon. However, Petrus et al. (2015) argued that the bolide was likely a 15 km diameter comet (density of 0.6 g/cm^3). If similar in composition to comet Halley, which has 18.4 wt% C (Delsemme 1988), the Sudbury object would have contained 195 Gt of C and, if fully vapourized, would have released ~700 Gt of CO_2 , or about one-third of the CO_2 perturbation of the current Anthropocene experiment (FIG. 3A).

In the lead-up to the impact, the continental foreland basin of the Lake Superior region was ferruginous, with thick banded-iron formations being deposited. Cannon et al. (2010) noted that the Sudbury impact layer nearly always caps the iron formations and other ferruginous sediment (FIG. 2) and that deposition continued with different mud-sized detritus. No re-occurrence of the dominant deposition of iron formation after the impact has yet been observed. There is, thus, strong regional evidence that the Sudbury impact event caused a sharp change in basin water conditions >700 km away. Noting that the disappearance of Palaeoproterozoic banded iron formation at ~1,850 Ma is a global phenomenon (FIG. 1), and further observing strong

evidence for tsunami deposits within some of the impact layers at variable water depths, Cannon et al. (2010) proposed that the Sudbury impact could have pervasively changed the regional, and probably the global, oceanic stratification, bringing to an end the long-lasting dominantly ferruginous state of the early Palaeoproterozoic deep oceans. The physical reasons for the inferred change remain to be established, however. It is currently unknown how an event such as the Sudbury impact could have disrupted the global oceanic iron supply and started the fickle oceanic states of the remaining Proterozoic.

The Sudbury Basin itself preserves the best-exposed and most accessible stratigraphy through a very large impact basin on Earth. It may originally have measured 170–200 km across but thanks to its remnant now being folded, there is an unparalleled opportunity to study transects from the shocked basement into the differentiated melt sheet and across the basin fill (e.g., Ubide et al. 2017) without the need for drilling. Of particular interest is the 1,300 m thick unit that overlies the crystallized melt sheet. It consists of breccias and tuffs that collectively are far too thick to represent the fallback from the impact. Instead, the first 300 m of chaotic breccias most likely formed through a fuel-coolant interaction, when seawater flooded onto the superheated melt sheet (e.g., Ubide et al. 2017). The remaining stratigraphy is characterized by sustained deposition of subaqueous volcanic products (bombs, lapilli and ash) that are more mafic than the average target rocks. The observation of on-going igneous activity within a subaqueous impact basin led Ubide et al. (2017) to speculate whether it could represent deeply sourced magmatism.

Numerical impact modelling (e.g., Collins et al. 2005) demonstrates that the depth of the transient cavity (created within less than a few seconds) nearly linearly increases with increasing bolide diameter (Fig. 3B), whereas the final depth of even a 500 km diameter basin is less than 3 km. The divergence in depth between transient cavity and final basin (Fig. 3B) necessitates an ever-increasing material flow during the rebound and collapse of the original cavity. It has been proposed (e.g., Jones et al. 2003) that the vertical component of this material flow could give rise to secondary decompression melting. In areas of unusually high continental heat flow (e.g., Sudbury) and on weak plates (e.g., ocean basins), one environmental consequence of very large impact events could, therefore, be sustained, deeply sourced magmatism and the associated release of volatiles.

Regardless of this possibility, a final noteworthy aspect of the Sudbury crater fill is the progressive enrichment of the breccias and tuffs in reduced carbon. Studying the chemistry of the fine-grained ash-sized matrix of the crater fill, O'Sullivan et al. (2016) demonstrated that the crater basin was likely cut off from the open ocean and so developed a distinctive water chemistry within it. These authors also note that the sustained magmatic activity within the basin supported base-metal deposition similar to volcanogenic massive sulfide ores, which otherwise occur at oceanic spreading sites. Apart from the destructive forces of very large impacts, one very different environmental consequence of subaqueous events could, thus, be the

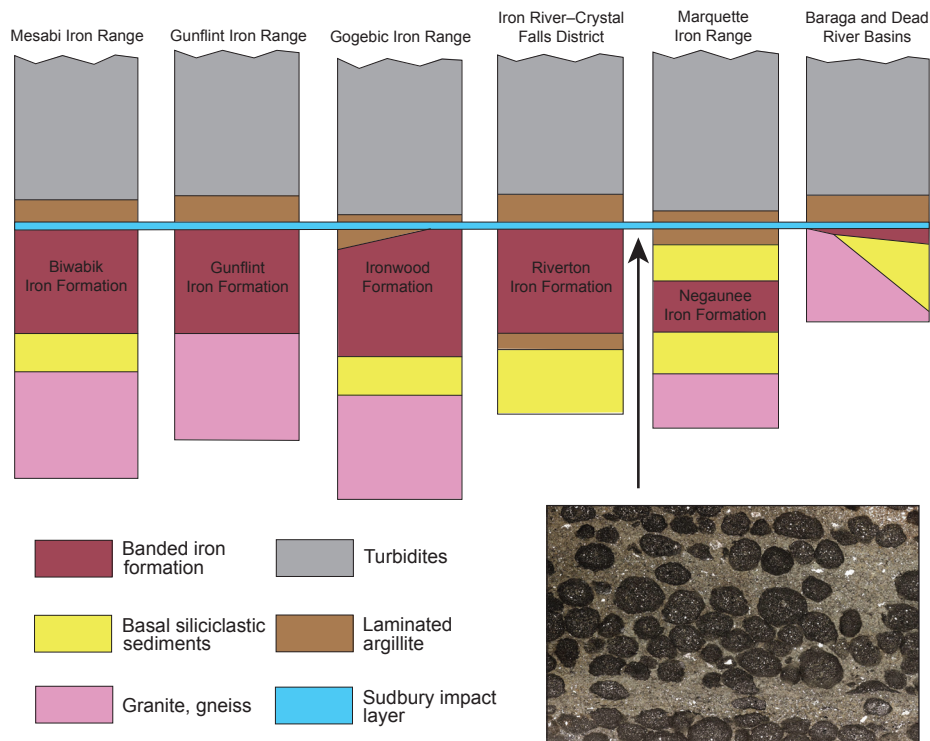


FIGURE 2 Stratigraphic relationship shown in six sedimentary logs between the Palaeoproterozoic Sudbury (Canada) impact layer (in blue) and the type of sediments that preceded and followed this event. Note the lack of deposition of banded iron formation after the impact event. The six logs relate to the following: Mesabi Iron Range (Minnesota, USA); Gunflint Iron Range (Minnesota, USA, and northwest Ontario, Canada); Gogebic Iron Range (Michigan and Wisconsin, USA); Iron River–Crystal Falls District (Michigan, USA); Marquette Iron Range (Michigan, USA); Baraga Basin and Dead River Basin (both in Michigan, USA). AFTER CANNON ET AL. (2010). (INSET) Example of a lapilli-stone, one of the rock types that makes up the Sudbury impact layer. The rock abounds with millimetre-sized accretionary lapilli that formed in the impact plume. Photo width is 5 cm.

formation of enclosed “ponds” (similar in shape to atolls), which contained chemical “factories” (hydrothermal systems) producing organic molecules as potential building blocks for life. Whereas life had long been established by 1,849 Ma, similar Hadean or early Archaean subaqueous impact basins should be considered as possible birth places of life and the kick-start of the terrestrial carbon cycle.

The ~590 Ma Acraman impact occurred during a period of intense fluctuations in the carbon cycle in the late Neoproterozoic Era (Fig. 1). The possibly 85–90 km diameter impact structure is now deeply eroded, but the corresponding impact layer can be traced for >500 km (Williams and Wallace 2003). Palaeomagnetic data suggest a low latitude impact, which could potentially increase any resultant environmental effects. But in terms of the on-going Neoproterozoic fluctuations in carbon isotopes (Fig. 1), the Acraman event seems to have been relatively minor, with only a small excursion towards a more negative reduced carbon isotope value; however, the detailed isotope stratigraphy is currently missing. Grey et al. (2003) pointed out that the Acraman impactite layer coincides with a marked change in fossil plankton (acritarch) successions and may have been more significant in terms of radiation than the preceding worldwide Marinoan glacial event (Cryogenian Period). The main target lithology of the Acraman impact were acidic volcanic rocks poor in carbon. There may have been limited disruption of the global carbon cycle, although detailed carbon isotope stratigraphy is unavailable.

THE CHICXULUB (MEXICO) IMPACT: A SPECIAL CASE OF BOMBARDING A PRODUCTIVE MARINE PLATFORM?

The remaining three largest terrestrial impact structures are Phanerozoic in age. The possible causal relationship between a large bolide impact and a Phanerozoic extinction event has been widely discussed in the literature, but there are two very clear observations (e.g., Fig. 1). One is that there have been more significant extinction events during the Phanerozoic than there are very large impact structures to account for them; the second is that there were large impact events [e.g., the 215 Ma Manicouagan crater in Quebec (Canada)] with no correlative mass extinction.

Against this backdrop, the exceptional coincidence between the K–Pg [formerly known as the K–T] extinction event and the ~180 km diameter, 66 Ma, Chicxulub impact structure in Yucatan stands out. It is still being debated whether the environmental effects of the bolide strike on their own were responsible for extinction or whether the Earth was struck at a time when its biology had already been pushed close to a tipping point by volcanic degassing and dropping sea-level. Regardless, it is widely agreed that the Chicxulub impact caused planet-wide climate disruption, as supported by the geological context of the impact site. In the late Cretaceous, the Yucatan Peninsula was a partially emerged platform composed of calcium carbonate and evaporite deposited on older sediments, themselves

sitting on Precambrian basement. The bolide excavated through this “fertile” stratigraphy at a site partly on land and partly submerged.

From a carbon cycle perspective, the presence of thick carbonate beds at the target site is of greatest relevance (Fig. 3A). The potential quantity of CO₂ devolatilized to high atmospheric altitude from bolides is dwarfed by that modelled to be ejected from a thick carbonate platform (Artemieva et al. 2017). On a 500–1,000 year timescale, the effects of releasing 425–1,400 Gt of CO₂ into the atmosphere (Artemieva et al. 2017; Brugger et al. 2017) is climate warming, but in the case of Chicxulub – where limestone, sulfate and seawater were the target – the short-term effect was dramatic SO₂-driven cooling with global annual mean surface air temperatures dropping by more than 20°C, recovering only after 30 years (Brugger et al. 2016). The bolide strike may also have caused massive wildfires and/or stratospheric emission of smoke from combustion of hydrocarbons within the target marine platform (oil and gas are produced to the north and west of the impact site). The nature of recovered molecules from incompletely combusted hydrocarbons preserved in the impact layer supports the idea that the bulk of the soot was released from reduced carbon contained within the impacted target rocks, amplifying SO₂-driven cooling along the equator and causing droughts (e.g., Kaiho and Oshima 2017). All this is consistent with the extinction patterns.

The K–Pg event, thus, emphasizes a further aspect of impacts on the terrestrial surface, which is lithologically and geochemically highly diversified and evolved. Less than one-sixth of the current planetary surface has a suitable make-up to cause strong stratospheric cooling if hit by a large bolide (Kaiho and Oshima 2017); significant direct disruption of the global carbon cycle seems only likely from impacts onto thick carbonate targets.

SUMMARY

Bolide impacts have affected the Earth’s carbon cycle in a multitude of ways. The widely held view that there are direct effects to the carbon cycle through environmental devastation and mass extinction, such as has been popularized with the K–Pg boundary event, is probably the exception rather than the rule. Most of the consequences of large impacts have been indirect. On the Hadean Earth, intense bombardment may have contributed to the destabilization of the original crust, thereby possibly promoting

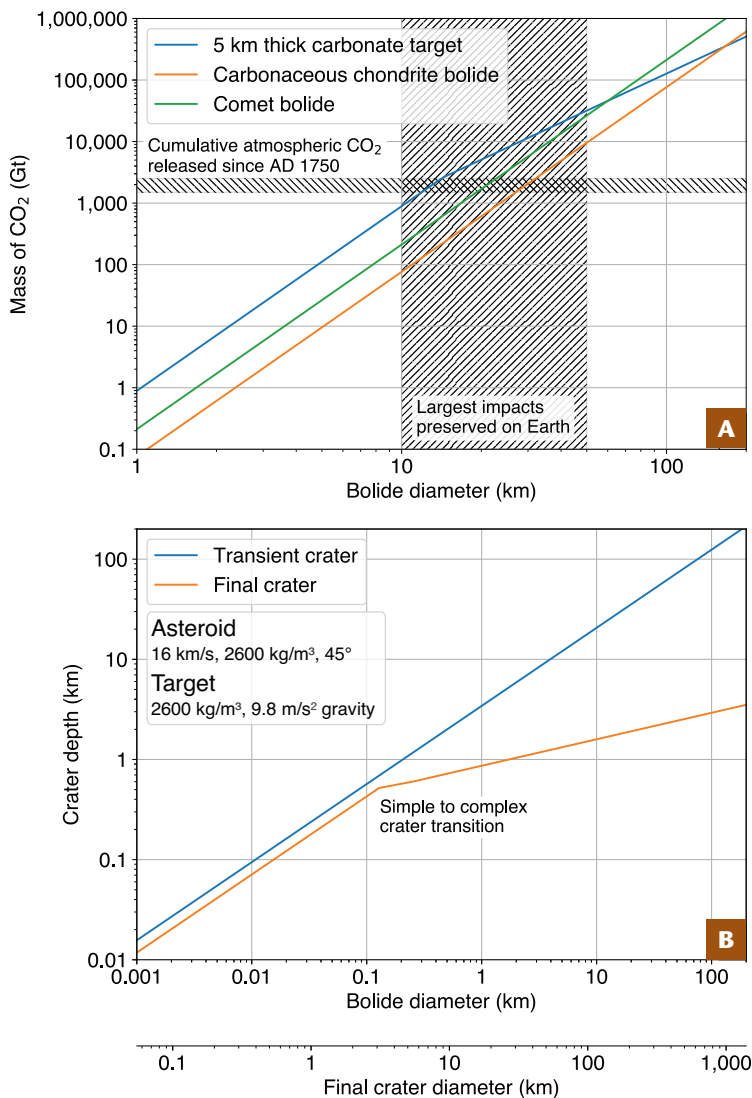


FIGURE 3 (A) Potential mass of CO₂ released as a function of bolide diameter for three scenarios. 1) Blue line – the impact of an ordinary chondrite into a 5 km thick carbonate target. AFTER ARTEMIEVA ET AL. (2017). 2) Orange line – a carbonaceous chondrite impacts into a carbon-free target, assuming a density of 2.2 g/cc and 1.81 wt% C. AFTER ALEXANDER ET AL. (2012). 3) Green line – a comet impacts into a carbon-free target, assuming a density of 0.6 g/cc and 18.1 wt% C. AFTER DELSEMMÉ (1988). Note that the curves shown for the carbonaceous chondrite (orange) and comet (green) assume total conversion of the contained C into global atmospheric CO₂ and are, therefore, overestimates. The cumulative atmospheric CO₂ released since AD 1750 (Anthropocene) is shown as a horizontal band centred at 2,000 Gt CO₂ (Boden et al. 2009). The largest impact events preserved on Earth (e.g., end-Cretaceous Chicxulub (Mexico); Archaean spherule layers) are shown as a vertical band between 10 km and 50 km. AFTER JOHNSON AND MELOSH (2012). (B) Transient impact crater depth (blue line) and final impact crater depth (orange line) as a function of final crater diameter and bolide diameter for a 2,600 kg/m³ asteroid travelling at 16 km/s striking a 2,600 kg/m³ target at 45° under the influence of Earth’s gravity. The kink in the final impact crater depth curve (orange) indicates the transition from simple bowl-like craters to complex craters collapsing and rebounding to form peak and/or ring structures. This transition stunts the growth of the final crater depth. The transient crater depth is likely an overestimate due to uncertainties about excavation, deformation, and displacement styles. Note that although the horizontal scale is the bolide diameter as in FIGURE 3A, the depicted ranges differ. DATA FROM COLLINS ET AL. (2005).

plate motion that has become an integral part of carbon cycling through plate destruction. Subaqueous early impact basins may also have been self-contained production sites of organic molecules that could have been potential cradles for life.

Throughout the Archaean, Earth continued to be occasionally bombarded by large bolides, as inferred from thick beds of spherules that must have splashed down from giant melt and vapour plumes. The existing Archaean sedimentary carbon isotope record does not appear to show fluctuations of the magnitude seen in later times: however, the record is of limited temporal resolution. In general, partitioning of carbon between the reduced and oxidized pools has remained surprisingly constant. The much more pronounced carbon isotope excursions of the Palaeoproterozoic and Neoproterozoic do not coincide with known impact events. Instead, the two very large events, at 1,849 Ma and 590 Ma, are traceable in the sedimentary record and are associated with the end of the deposition of banded iron formations and the radiation of acritarch plankton, respectively. If future work demonstrates these to be causal relationships, they would illustrate the indirect influence of large impacts on the carbon cycle through the reorganisation of the ocean's redox state and the disruption of biological evolution.

REFERENCES

Alexander CMO'D and 5 coauthors (2012) The provenances of asteroids, and their contributions to the volatile inventories of the terrestrial planets. *Science* 337: 721-723

Artemieva N, Morgan J, Expedition 364 Science Party (2017) Quantifying the release of climate-active gases by large meteorite impacts with a case study of Chicxulub. *Geophysical Research Letters* 44: 10,180-10,188

Boden TA, Marland G, Andres RJ (2009) Global, regional, and national fossil-fuel CO₂ emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, doi: 10.3334/CDIAC/00001_V2010

Bottke WF, Norman MD (2017) The late heavy bombardment. *Annual Review of Earth and Planetary Sciences* 45: 619-647

Bottke WF and 7 coauthors (2012) An Archaean heavy bombardment from a destabilized extension of the asteroid belt. *Nature* 485: 78-81

Brugger J, Feulner G, Petri S (2017) Baby, it's cold outside: climate model simulations of the effects of the asteroid impact at the end of the Cretaceous. *Geophysical Research Letters* 44: 419-427.

Cannon WF, Schulz KJ, Horton JW Jr, Kring DA (2010) The Sudbury impact layer in the Paleoproterozoic iron ranges of northern Michigan, USA. *Geological Society of America Bulletin* 122: 50-75

Collins GS, Melosh HJ, Marcus RA (2005) Earth Impact Effects Program: a Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth. *Meteoritics & Planetary Science* 40: 817-840

Delsemme AH (1988) The chemistry of comets. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences* 325: 509-523

Eigenbrode JL, Freeman KH (2006) Late Archean rise of aerobic microbial ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* 103: 15,759-15,764

Grey K, Walter MR, Calver CR (2003) Neoproterozoic biotic diversification: Snowball Earth or aftermath of the Acraman impact? *Geology* 31: 459-462

Grieve RAF, Stöffer D (2012) Impacts and the Earth: a perspective. *Elements* 8: 11-12

Johnson BC, Melosh HJ (2012) Impact spherules as a record of an ancient heavy bombardment of Earth. *Nature* 485: 75-77

Jones AP, Price DG, DeCarli PS, Price N, Clegg R (2003) Impact decompression melting: a possible trigger for impact induced volcanism and mantle hotspots? In: Koerber C, Martínez-Ruiz FC (eds) *Impact Markers in the Stratigraphic Record*. Springer, Berlin, pp 91-119

Kaiho K, Oshima N (2017) Site of asteroid impact changed the history of life on Earth: the low probability of mass extinction. *Scientific Reports* 7, doi: 10.1038/s41598-017-14199-x

Kamber BS (2015) The evolving nature of terrestrial crust from the Hadean, through the Archaean, into the Proterozoic. *Precambrian Research* 258: 48-82

Krissansen-Totton J, Buick R, Catling DC (2015) A statistical analysis of the carbon isotope record from the Archean to Phanerozoic and implications for the rise of oxygen. *American Journal of Science* 315: 275-316

Kyte FT, Shukolyukov A, Lugmair GW, Lowe DR, Byerly GR (2003) Early Archean spherule beds: chromium isotopes confirm origin through multiple impacts of projectiles of carbonaceous chondrite type. *Geology* 31: 283-286

Lowe DR, Byerly GR, Kyte FT (2014) Recently discovered 3.42-3.23 Ga impact layers, Barberton Belt, South Africa: 3.8 Ga detrital zircons, Archean impact history, and tectonic implications. *Geology* 42: 747-750

Most Phanerozoic mass extinctions are not coincident with very large impact events. The Chicxulub event, occurring at the K-Pg boundary, caused a moderate carbon isotope excursion and greatly disrupted the budget of climate-active gases in the atmosphere. This, in turn, led to a short-term abrupt cooling and a medium-term strong warming (e.g., Brugger et al. 2016). The lesson drawn for the Anthropocene is that the release of several thousand Gt of CO₂ into the atmosphere may not leave a marked carbon isotope signal in the geological record. Instead, the Anthropocene is more likely to leave its legacy as a mass extinction from greenhouse-induced climate change on a biosphere already at a tipping point caused by habitat loss.

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Morbidelli A and 7 coauthors (2018) The timeline of the lunar bombardment: revisited. *Icarus* 305: 262-276

O'Sullivan EM, Goodhue R, Ames DE, Kamber BS (2016) Chemostratigraphy of the Sudbury impact basin fill: volatile metal loss and post-impact evolution of a submarine impact basin. *Geochimica et Cosmochimica Acta* 183: 198-233

Petrus JA, Ames DE, Kamber BS (2015) On the track of the elusive Sudbury impact: geochemical evidence for a chondrite or comet bolide. *Terra Nova* 27: 9-20.

Peucker-Ehrenbrink B, Ravizza G, Winckler G (2016) Geochemical tracers of extraterrestrial matter in sediments. *Elements* 12: 191-196

Reimold WU, Jourdan F (2012) Impact! – Bolides, craters, and catastrophes. *Elements* 8: 19-24

Rothman DH (2017) Thresholds of catastrophe in the Earth system. *Science Advances* 3, doi: 10.1126/sciadv.1700906

Schidlowski M, Appel PWU, Eichmann R, Junge CE (1979) Carbon isotope geochemistry of the 3.7 × 10⁹-yr-old Isua sediments, West Greenland: implications for the Archaean carbon and oxygen cycles. *Geochimica et Cosmochimica Acta* 43: 189-199

Simonson BM, Glass BP (2004) Spherule layers—records of ancient impacts. *Annual Review of Earth and Planetary Sciences* 32: 329-361

Tera F, Papanastassiou DA, Wasserburg GJ (1974) Isotopic evidence for a terminal lunar cataclysm. *Earth and Planetary Science Letters* 22: 1-21

Ubide T and 7 coauthors (2017) Protracted volcanism after large impacts: evidence from the Sudbury impact basin. *Journal of Geophysical Research: Planets* 122: 701-728

Williams GE, Wallace MW (2003) The Acraman asteroid impact, South Australia: magnitude and implications for the late Vendian environment. *Journal of the Geological Society* 160: 545-554 ■