LARGE BOLIDE IMPACTS - IS IT ONLY SIZE THAT COUNTS?

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ABSTRACT

Just one well documented large terrestrial impact, the end Cretaceous Chicxulub event, can be linked to a mass extinction. Other well-constrained large impacts, evidenced by craters in the region of 100km or more, have been implicated in extinction but either their exact timing or the independent biodiversity data fail to clinch the link. By breaking down impact events into their component effects and separately assessing their biotic damage we can get nearer to a true risk assessment. We conclude that a major reason for some large impacts being apparently "safe" relates as much to where they struck, what they struck and when, as to how large the events were as revealed by crater size.

1. INTRODUCTION

In estimating the biotic effects of large impacts great reliance is usually placed on apparent crater size. Raup's [1] definitive "Kill Curve" explicitly linked crater diameter with extinction numbers, and later modifications by Jansa et al [2] and Poag [3] sought to determine just what size of impact, implied by crater size, was necessary to be catastrophic for the planet as a whole (Fig. 1). However, the model is based on a very small statistical sample (only one well known Phanerozoic impact has been credited with substantial and immediate biotic effects) and apparent crater diameter alone is an unreliable proxy for the environmental and biotic consequences of an impact. Risk of extinction stems from a number of factors (Fig.2) and having regard for crater diameter alone ignores variables such as location (environment, plate tectonic setting, site geology ("Where" in Fig. 2) and timing in relation to biological and geological evolution ("When" in Fig. 2).

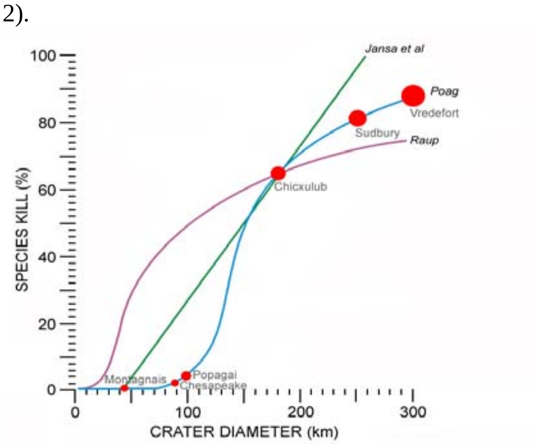

Fig. 1. The Raup Kill Curve (labeled) with subsequent modifications by Poag.

2. SIZE VERSUS LOCATION AND TIMING

There are around 170 well constrained and documented terrestrial craters larger than 1km, only one of which, the c.170km end Cretaceous Chicxulub crater in Mexico, has been justifiably linked to a major extinction. Crater diameter is usually the only information we have upon which to estimate the scale of an impact and uncertainty is increased through the effects of erosion, deposition or tectonism that have deleted large parts of the record.

Size is broadly related to bolide mass, velocity and impact angle ("What" and "How"; Fig, 2), but the location of an impact can also affect size. For example, a substantial depth of water can reduce apparent crater diameter (many terrestrial impacts must have been marine), whilst the architecture and rheology of shallow site geology can cause an increase in apparent size through the development of collapse structures.

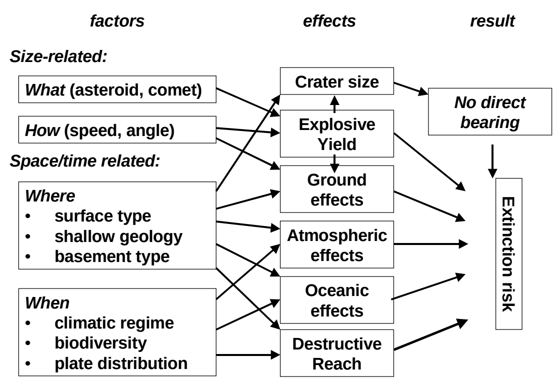

Fig. 2. Factors contributing to risk of Extinction.

We propose that in the critical size range of consideration by Raup (say, 30 to 300km), two strong determinants on the extinction potential of an impact are where it struck and when (Fig. 2). To test this, we have looked in some detail at our two best - documented large terrestrial craters. These are the c.170km end Cretaceous Chicxulub impact structure, Mexico (linked to a major extinction), the c.100km late Triassic Manicouagan structure, NE Canada (negligible extinction).

Both craters point up the complexity of the key piece of data upon which the Kill Curve depends - namely the acurate determination of the final crater diameter. Chicxulub is now completely obscured. It was excavated through an unstable carbonate platform into a subsiding (and also potentially unstable) continental margin. It is now buried by up to 1km of post Cretaceous sediment. Manicouagan, on the other hand, was formed in a thick high- strength ancient continental interior. Exposed since the Triassic, the original crater morphology and all proximal ejecta have been lost to erosion, together with >1km of the underlying crust. The structure is now eroded down to c.65% of an original 100km diameter.

More usefully, Chicxulub and Manicouagan provide locational and environmental extremes. Although they both struck the planet at between 20^0N and 25^0N, Chicxulub zeroed on a humid subtropical marine embayment next to wide expanses of high biodiversity continent and ocean, whilst Manicouagan struck well within the arid interior of the massive Pangean supercontinent, well away from oceans and forest. The Manicouagan impact also caught the planet at a time of relatively low world-wide biodiversity. It might be said that whilst the late Cretaceous sub tropical belt was a highly vulnerable target, the late Triassic continental interior was already the sort of barren extreme that a large impact might create. It therefore is of little surprise that, independent of their actual size, the Chicxulub and Manicouagan events had such contrasting biotic effects.

3. MODELLING AND REVERSE-MODELLING CHICXULUB AND MANICOUAGAN

We have modelled some of the probable effects of the Chicxulub and Manicouagan using a combination of existing mathematical models [4-14] to arrive at a link between crater diameter and potentially lethal distal effects such as radiation, firestorms, pressure, wind and dust fallout. The mathematics are adopted as published and are incorporated into an holistic spreadsheet without further critical review. The spreadsheet presently permits two calculations to be run simultaneously and side-by-side (Fig. 3) and is easily modified and extended.

The calculations derived in this way have been used to inform a semi quantitative table (Fig.4) that lists the principal hazards associated with the respective impacts from the local scale to the global.

These hazards are briefly detailed as follows:

Cratering

The bolide strikes at between 11 and 72 km/s; rock bolides being in the lower part of this range. Kinetic energy release vaporises, melts and pulverises rocks at ground zero, excavating a crater up to 20x the diameter of the impactor. The crater partly refills through return of ejecta and slumping of sides. Local obliteration of biota is guaranteed.

	BOLIDE A	BOLIDE B
Impactor diameter m	**9000**	**15000**
Impactor density kg/m3	**2750**	**2750**
Impactor velocity km/s	**20**	**20**
Kinetic Energy J	2.09937E+23	9.7193E+23
Entry Angle	**75**	**75**
Water thickness m	**0**	**0**
Target density	**2750**	**2750**
Transient Water Crater (m)	0	0
Transient Rock Crater (m)	59579	88758
Crater "rim-to-rim" final (km)	102	160
Avg Rim-to-Floor depth (km)	1.60	1.83
Melt Volume km3)	1801	8345
Melt thickness in crater (m)	646	1349
Fireball radius (m)	118787	198031
Max pulse seconds after impact (s)	6	10
Location Distance (km)	**2000**	**2000**
Iradiation duration (s)	1544	2573
Thermal exposure at location (J)	0	0
Trees Burn from plume radiation?	NO	NO
Siesmic Effect (Richter Scale)	4.2	4.6
Arrival time (s)	400	400
Ejecta Thickness (mm)	14.1	69.3
Peak overpressure Pa	32196.1	66423.1
Peak wind velocity MPH @	150	280

Summary / Background A / Background B / Background C / Background D /

Fig. 3. Sample section from spreadsheet used to calculate and compare the distal effects of two different impactors at a range of possible impact site conditions (equations used are derived from numerous authors and are acknowledged in text). This run models a Manicouagan - scale and a Chicxulub - scale impact at the Manicouagan site. The distance from impact chosen here represents that of the distal impact deposit from Manicouagan reported by Walkden et al.[ ]

Shock/Blastwave

An atmospheric pressure pulse of c.4-psi centred on the impact site is followed by winds of >250 km/h. Blast radiates and blows off the atmosphere between 140° and tangentially to the curvature of the Earth. Regional devastation of biota takes place.

Ejecta curtain

A corona of gaseous and molten ejecta rises and expands on a ballistic trajectory. This leaves a thick melt sheet proximally and a torrent of condensing glass droplets distally (microtektites). Local obliteration and regional devastation of biota are assured.

Fireball and Plume

A plume of ejecta erupts from the cratering process beyond the level of the earth’s atmosphere. Material enters orbital and suborbital paths re-entering proximally to distally (perhaps antipodally) with associated IR radiative effects. No direct plume-related deleterious effects on biota.

Atmospheric surge

Atmosphere is sheard away locally by the expanding blast. Compression and displacement of atmospheric gases outwards is replaced by a counterflow. Supercanes occur proximally, atmospheric destratification is general. Damage to biota is related to regional hypervelocity winds and local atmospheric depletion.

4a. "Actual"	Chicxulub	Manicouagan
Bolide: rock *Crater diameter* *Latitude*	c. 15km c. 170km - 20-25^{0}N	c. 10km c. 100km 20-25^{0}N
shallow geology deep geology	unstable carbonate shelf subsiding plate margin	thin Palaeozoic cover stable high-strength craton
Continent configuration	dispersed E-W	assembled N-S
Surface type *Climate*	marginal marine sub tropical humid	continental dryland sub tropical arid
Regional biodiversity *Global biodiversity*	high high	low moderate

EFFECT		Chicxulub: Approx. biotic damage		Manicouagan: Approx. biotic damage
Cratering	LOCAL	V	LOCAL	V
Shockwave	LOCAL	IV	LOCAL	III
Ejecta curtain	LOCAL	IV	LOCAL	III
Plume/ Fireball	LOCAL	I	LOCAL	I
Atmospheric surge	REGIONAL	II	REGIONAL	II
Seismic wave series	REGIONAL	II	REGIONAL	I
Tsunami	REGIONAL	III	REGIONAL	
Shelf wasting	REGIONAL	III	REGIONAL	
Plume fallout	GLOBAL	I	GLOBAL	I
IR radiation	GLOBAL	III	GLOBAL	I
Suspended dust	GLOBAL	III	GLOBAL	II
Wildfires	GLOBAL	III	GLOBAL	
Wildfire soot	GLOBAL	III	GLOBAL	
CO/CO_2	GLOBAL	III	GLOBAL	I
SO_2	GLOBAL	II	GLOBAL	
NO_2	GLOBAL	II	GLOBAL	I
CH_3	GLOBAL	II	GLOBAL	

4b. Reversed	Chicxulub	Manicouagan
Bolide: rock *Crater diameter* *Latitude*	c. 9km c.100km - 20-25^{0}N	c.15km c.170km 20-25.8^{0}N
shallow geology *deep geology*	unstable carbonate shelf subsiding plate margin	Thin Palaeozoic cover stable high-strength craton
Continent configuration	dispersed E-W	assembled N-S
Surface type *Climate*	marginal marine sub tropical humid	continental dryland sub tropical arid
Regional biodiversity *Global biodiversity*	high high	low moderate

EFFECT		Chicxulub: Approx. biotic damage		Manicouagan: Approx. biotic damage
Cratering	LOCAL	V	LOCAL	V
Shockwave	LOCAL	IV	LOCAL	IV
Ejecta curtain	LOCAL	III	LOCAL	IV
Plume/ Fireball	LOCAL	I	LOCAL	I
Atmospheric surge	REGIONAL	II	REGIONAL	II
Seismic wave series	REGIONAL	I	REGIONAL	I
Tsunami	REGIONAL	II	REGIONAL	?
Shelf wasting	REGIONAL	II	REGIONAL	?
Plume fallout	GLOBAL	I	GLOBAL	I
IR radiation	GLOBAL	II	GLOBAL	II
Suspended dust	GLOBAL	II	GLOBAL	III?
Wildfires	GLOBAL	II	GLOBAL	I
Wildfire soot	GLOBAL	I	GLOBAL	I
CO/CO_2	GLOBAL	II	GLOBAL	I
SO_2	GLOBAL	II	GLOBAL	
NO_2	GLOBAL	I	GLOBAL	I
CH_3	GLOBAL	I	GLOBAL	?

Fig. 4. Modelling biotic damage arising from the effects of the Chicxulub and Manicouagan impacts.
4a: Probable biotic damage based upon actual crater diameter, target structure, target composition, continental massing, ambient biodiversity and environmental conditions at the time and location of the two impacts (toned columns; these reflect an estimate of damage arising from each effect between 0 and V with 5 high. Colour density is arranged accordingly).
4b: Modelled biotic damage based upon interchanged energy output of the impacts (blue highlight). Other parameters remain as in 4a. Note that even under reversed modelling, where the smaller impactor strikes at Chicxulub and the larger impactor strikes at Manicouagan, Chicxulub marginally remains the more lethal event.

Seismic waves
Ground zero earthquake exceeds force 10 by orders of magnitude and spreads across the globe. Secondary earthquakes and tsunamis are triggered. Biotic depletion almost anywhere.
Tsunami
Marine impacts generate giant primary Tsunami. Secondary ones follow crater refilling and waves oscillate across oceans. Oceanic circulation can break down. Biotic devastation takes place on shelves and coastal plains.
Shelf wasting
Cratering, tsunami and seismic shaking produce mass wasting of shelves and release of shelf gas hydrates. Severe biotic effects from resuspension, slumping and mass flow. Benthic zones affected and as far as 100's km from ground zero.
Plume fallout
The rising plume of vapour, melt and pulverised rock collapses, returning groundwards to produce pyroclastic flows, dust storms and debris flows. Biotic effects are limited to areas already affected by other devastation.
IR radiation
Frictional heating of re-entering ejecta produces infra-red radiation. Ground surface heats to 200-300° C. Biotic damage limited to dessiccation (see below for wildfires) but might be sub global. Devastation is dependent on ejecta volume and dynamics.
Wildfires
The landfall of hot re-entered ejecta on IR-desiccated flora can ignite ravaging wildfires. Severe biotic effects sub-globally, but mostly limited to areas of desiccation.
Dust
Suspended dust can remain in the atmosphere for weeks or months. Severe light and heat reduction are implicit. Biotic effects are dependent on duration, potentially affecting whole food chains worldwide.
Soot
Large volumes can be thermally lofted from forest and grassland wildfires. Widespread dispersal is by winds and atmospheric circulation. Temperature effects are disputed and uncertain. Biotic damage takes place through disruption of atmospheric heat budgets, low light levels and changes to weather and climatic patterns.
H_2O (not modelled)
Marine impacts eject large volumes of water into the atmosphere. Long term residence in the upper atmosphere will have greenhouse and general climatic effects, but worldwide rainout of soot and dust is likely. Biotic effects are unpredictable.
CO_2 / CO
CO_2 from dissociation of carbonates is possible. CO_2 from wildfire combustion is likely. Biotic effects stem from resultant greenhouse warming.
SO_2
Sulphur dioxide from evaporites in the impact site rock column could be produced in large volumes. Oxidised, and coupled with water in the upper atmosphere, this creates sulphuric acid, then acid rain. Severe biotic effects have been claimed for both terrestrial and marine areas worldwide.
NO_2
Shock heating of outer atmosphere by re-entering material can produce Nitric Acid, Biotic effects similar to SO_2, and are dependent on volume.
CH_3
Oceanic disturbances (including tsunami, slumps, and temperature change) can destabilise gas hydrates and release large volumes of methane. This is a greenhouse gas and reacts to create ozone that can become toxic in large quantities.

Useful discussions of most of these effects can be found in [16-18].

Informed by numerical modelling in the spreadsheet (eg. Fig 3) we go on to analyse each effect noted above for its potential biotic damage (Fig. 4). Severity is scored on a subjective scale of 0-5(V) with 5 high. These estimates are tone-coded for direct visual comparison from low (light) to high (dense). At the moment some significant effects noted in the tables are only approximations informed by the nearest factor in the spreadsheet. Continued development of the spreadsheet (Fig. 3) should achieve better correspondence between this and the assessments of hazard (Fig. 4). At that stage we intend to make the spreadsheet available on the internet.

We first model Chixculub and Manicouagan using values to match their apparent actual crater diameters (Fig. 4a). Then, to test the influence of location, we have reversed the craters, showing the effects of a Chicxulub - scale impact at Manicouagan and a Manicouagan - scale impact at Chicxulub (Fig. 4b). Although the diameters of the two craters are arguably in the same order of magnitude, the energy release at Chicxulub was as much as five times that at Manicouagan (Fig.3). Nonetheless, there are substantial differences between the two events relating to location and timing that strongly influence the modelling. These include target structure, target composition, massing of continents, ambient biodiversity, and environmental conditions (noted in Fig. 4). These locational and timing factors lead to a strong contrast in predicted biotic effects from the two impacts (Fig. 4a). However, after reversing the the craters and despite their size difference the modelling suggests that, instead of completely reversing the biotic effects, there would have been very little difference between them in terms of biotic effects (Fig 4b). What emerges from this is that, to the extent that the Chicxulub event was "unlucky" through its location and timing, Manicouagan was "lucky". The following factors served to reduce the biotic effects of the Manicouagan event and probably saved it from becoming a planetary disaster:

- lower general and local biodiversity in the Trias

- the high crustal strength and stability of the Manicouagan site
- the lack of a substantial thickness of rocks at the impact site capable of generating potentially lethal volatiles (eg. CO, CO_2, SO_2)
- the location of the impact in a climatically inert arid continental belt.
- the pre-adaptation of the animal and plant population in this belt to a climatic extreme comparable to post-impact conditions
- the location of the impact at the centre of a supercontinent well remote from oceans and seaways
- the massing of continents in a N-S direction so that the east-west smearing of re-entering fallout mainly dissipated over ocean.
- the position of the antipodal site (the location of any antipodal re-entry of ejecta, eg. [19]). over ocean.
- Westward smearing from the above mainly affecting the southern continental arid belt.
- the lack of ignitable Triassic forest ecosystems in mid latitude regions where the main fallout and re-entry effects were concentrated.

4. CONCLUSIONS AND RECOMMENDATIONS

Impact site variables such as geological structure of the target, composition of the target rocks, the position of a target in plate tectonic terms, the massing of continents at the time of the impact, regional paleoclimatic conditions, ambient biodiversity, trophic structure and the local paleoenvironment at the time of the impact have a strong influence on the "kill potential" of an impact event. Size of an impact alone is not a reliable indicator of biotic effects.

Two of our best known and age-constrained craters, The 100km late Triassic Manicouagan crater and the c.170km end Cretaceous Chicxulub crater were both large and potentially lethal environmental traumas. They represent extremes in terms of the impact site variables noted and they were extremes in terms of their biotic effects. Chicxulub has been implicated in an extinction event that depleted species by c. 65%, whilst a convincing extinction effect is yet to be demonstrated with respect to Manicouagan.

The modelling procedures we have employed require further refinement before they can be applied rigorously and predictively. What we have shown is that, by combining the output of existing mathematical models for predicting proximal and distal effects of an impact with a systematic assessment of an impact event factor by factor, an holistic picture of the biotic effects of an impact will emerge. This is, effectively, an early stage in the development of a systematic risk assessment procedure for ancient impacts.

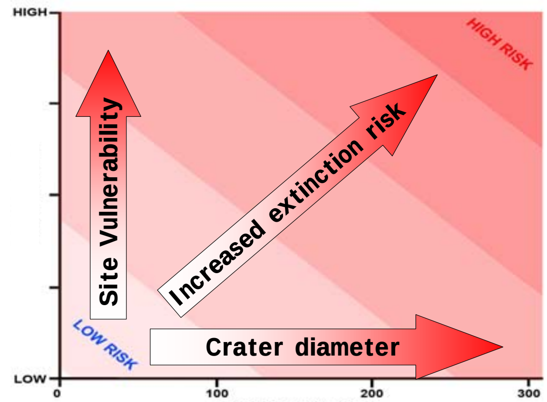

Fig. 5 New "Risk" diagram, with size plotted against environmental and/ or locational factors ("vulnerability").

Our modelling exercise confirms that location and timing of an impact are significant variables with potentially strongly determinant effects on biotic consequences. Size alone is an insufficient measure of the likely biotic effects of a bolide impact event and few extinction specialists would continue to support the simple Kill Curve approach. Ultimately, it reflects only superficial data and cannot be used analytically or predictively. Instead, we are developing a more sophisticated means of diagrammatically expressing "kill potential" in terms of an expression of risk, related both to size and site vulnerability (Fig 5). This, together with an extended analysis of some large impact events will be published elsewhere.

5. REFERENCES

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