Chicxulub distal ejecta: modelling versus observations

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Motivation

Model the ejection of material from Chicxulub around the globe to form the K-P boundary layer

Approach

Identify observational data that are well constrained

Model a range of Chicxulub impact scenarios, and investigate which models best reproduce the observational data
Talk outline

**Observational data:** 5 first-order observations

**Numerical Modelling:** results for impacts with different masses, velocities, impact angles, and target (wet and dry), all with ballistic transport from the impact site to final destination

**Result:** 3 observations well matched, two observations cannot be reproduced

Look at a possible non-ballistic mechanism for transport
Haiti (~900 km from Chicxulub)
Composition spherules: mix mafic rocks and Ca-rich sediments (proportion unclear)

Basal unit thought to be ballistic ejecta
20-30 cm thick ~25% glass spherules (50% if include altered spherules)

Observation 1
5-15 cm thick layer glass spherules at ~900 km

Hildebrand and Boyton 1990; Sigurdsson et al., 1991; Carey et al., 1993; Smit, 1999.

Observational data: Proximal ejecta
Observational data: Distal ejecta layer

**Observation 2**  
2.0 - 2.8 x 10^8 kg Ir (assumes 40-55 ng per cm², Kyte 2004)

**Observation 3**  
~850 km³ spherules (total layer volume 1000-1500 km³)

**Observation 4**  
layer thickness roughly constant (2 - 3 mm)

K-Pg sites (redrawn from Claeys et al. 2002)
Observation 5

Shocked quartz vol. 0.02-0.05 km³

Nos and size of shocked quartz decreases with paleodistance from Chicxulub

Quartz (and zircon) originate from Chicxulub basement

Compiled by Cristiano Lana (Morgan et al., 2006)
Numerical modeling

1) Impact crater modeling and material ejection (SOVA-3D)
2) Fragmentation, interaction with plume and/or atmosphere (SOVA-3D)
3) Ballistic motion in upper atmosphere

Use 1-3 to determine composition and volume of ejecta that:
- escapes the Earth;
- forms the proximal and distal ejecta;
- stays at/or close to the impact site.

Chicxulub
Impactor density: 2600 kg/m³. Target: 3 km sediments, 30 km crust above mantle (EOS for calcite, granite dunite). Wet target has 30% porosity

<table>
<thead>
<tr>
<th></th>
<th>Diameter (km)</th>
<th>Velocity (km/s)</th>
<th>Angle</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.4</td>
<td>18</td>
<td>45°</td>
<td>Dry</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>18</td>
<td>30°</td>
<td>Dry</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>36</td>
<td>45°</td>
<td>Dry</td>
</tr>
<tr>
<td>4</td>
<td>14.4</td>
<td>18</td>
<td>45°</td>
<td>Wet</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>18</td>
<td>90°</td>
<td>Wet</td>
</tr>
</tbody>
</table>

All models reproduce observed size of Chicxulub crater (~100 km diameter transient cavity)
Proximal ejecta – Haitian glasses

Observed glass spherule thickness
5-15 cm at 900 km distance

Observation 1: √
Volume glass spherules is roughly correct
- Outermost part of plume at 200 km altitude consists of high velocity ejecta formed from projectile and sediments
- Basement material has reached a maximum altitude of 70 km and has a maximum velocity of < 3 km/s
Thus – no basement material has sufficient velocity to reach distal sites

NO models lead to shocked quartz in distal layer

Observation 5: X

Observed shocked quartz vol. 0.02-0.05 km$^3$. 

Thus – no basement material has sufficient velocity to reach distal sites

NO models lead to shocked quartz in distal layer

Observation 5: X
### Calculation iridium mass assumes 500 ng/g iridium in projectile

<table>
<thead>
<tr>
<th>Model</th>
<th>Distal ejecta &gt; 5 km/s and &lt; escape (as fraction of projectile)</th>
<th>Iridium mass (x 10^8 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 14.4 km, 45°, 18 km/s, dry</td>
<td>0.14</td>
<td>2.8</td>
</tr>
<tr>
<td>2. 16 km, 30°, 18 km/s, dry</td>
<td>0.34</td>
<td>9.3</td>
</tr>
<tr>
<td>3. 10 km, 45°, 36 km/s, dry</td>
<td>0.41</td>
<td>2.8</td>
</tr>
<tr>
<td>4. 14.4 km, 45°, 18 km/s, wet</td>
<td>0.17</td>
<td>3.5</td>
</tr>
<tr>
<td>5. 12 km, 90°, 18 km/s, wet</td>
<td>0.03</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Sub-vertical impact – too little iridium in the distal ejecta
≤ 30 degree impact – too much iridium in the distal ejecta

45° impact angles roughly reproduce observed iridium  Observation 2: √
### Assumes all high-velocity ejecta in plume forms spherules

<table>
<thead>
<tr>
<th>Model</th>
<th>Spherule volume in distal ejecta (km³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 14.4 km, 45°, 18 km/s, dry</td>
<td>760</td>
</tr>
<tr>
<td>2. 16 km, 30°, 18 km/s, dry</td>
<td>1630</td>
</tr>
<tr>
<td>3. 10 km, 45°, 36 km/s, dry</td>
<td>1080</td>
</tr>
<tr>
<td>4. 14.4 km, 45°, 18 km/s, wet</td>
<td>800</td>
</tr>
<tr>
<td>5. 12 km, 90°, 18 km/s, wet</td>
<td>55</td>
</tr>
</tbody>
</table>

≤ 30 degree impact spherule volume a bit large
Sub-vertical– spherule volume much too small

45° impact angles roughly reproduce observed spherule volume  Observation 3: √
Total volume for 45 degree impacts is roughly correct.

But ejecta layer thickness is not constant

Observation 4: X

All models that involve ballistic travel from impact site to final location lead to a gradual decrease in ejecta thickness with distance.
Modelling Summary

Observations 1 – 3 (proximal ejecta, iridium, distal spherule volume): √

Observations 4 - 5 (shocked quartz, layer thickness) X

- No shocked quartz reaches distal sites
- Layer thickness not constant

Pure ballistic transport of the ejecta cannot explain two first-order properties of the distal ejecta.
Non-ballistic transport

As ejecta re-enters the atmosphere, the atmosphere heats up and expands, re-distributing the ejecta.

Termed “Floating debris” by Colgate and Petschek (1985)

Here, we model a beam of ejecta with total volume of material equivalent to that arriving ~1000 km from Chicxulub as it re-enters the atmosphere (using SOVA 3D)
Large particles (1 cm) pass straight through the atmosphere.

1 mm particles are dispersed 500 km downrange.

Small particles (0.1 mm) are dispersed ~1000 km uprange and downrange.

Model beam of ejecta with three particles sizes:
- Haitian spherules ~0.5 cm,
- Average spherule ~0.25 mm,
- Mean-size quartz ~0.1 mm.

Figure 2: Re-distribution of ejecta through atmospheric heating.
Final ejecta distribution for this model

Large particles form bulk of 2 cm thick layer in middle

Smaller particles are re-distributed to form 1-2 mm thick layer of fairly constant thickness

Approximately 1/3 of particles fall outside model

Colored squares are final ejecta thickness (14 cm) without re-distribution by expanding atmosphere
Conclusions 1

Non-ballistic transport (floating debris) could allow low velocity ejecta to travel around the globe and thus reproduce:

- Shocked quartz in distal ejecta layer (with no annealing)
- Size distribution of shocked quartz
- Relatively constant layer thickness

Observations 4 - 5 ✓
Ballistic and non-ballistic ejecta may arrive at distal sites at ~same time

e.g. for Europe:

- Ballistic ~20 mins to top atmosphere, 5-30 hours in atmosphere (coarse first)
- Non-ballistic, a few hours to site (fine first), a few hours in atmosphere
Distal ejecta travels by two mechanisms:

1) Ballistic, high-velocity, projectile-rich ejecta forms Ir-rich (spinel-bearing) spherules.

2) Shocked quartz and Ir-poor spherules transported non-ballistically by “floating debris” mechanism.

Observations 1 - 5 √

Artemieva and Morgan, Icarus, in press