The geophysical signature of impact craters

Stephanie Werner
Observation, geophysical techniques and implications

- Gravity Anomalies
- Magnetic Anomalies
- Seismic profiling
- Electrical / Electromagnetic
- Magnetotelluric
- Ground Penetrating Radar
- Radiometric
- ...
Crater Formation Process

A. Excavation stage (the sole stage for a simple crater).

- ejecta
- rarefaction (release) wave
- shock wave
- direction of material flow
- melt
- rebound
- downward faulting

B. End of excavation stage; start of modification stage.

- rebound

C. Continuation of modification stage.

- descending ejecta

D. Final structure.

- ejecta blanket
- melt layer
- central peak
- terraces of collapsed material

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Observations: Physical

Shape: circular features

Inverted Stratigraphy:
first recognized by Barringer (only for well preserved craters)

Material displacement:
Solid material broken up and ejected outside the crater: breccia, tektites
Observations: Shock Evidence

Shatter cones:
conical fractures with typical markings produced by shock waves

Shocked Material:
shocked quartz
high pressure minerals

Melt Rocks:
may result from shock and friction
Observations: Geophysical data

Gravity anomaly:
based on density variations of materials

Magnetic:
based on *general* variation of magnetic properties of materials

Seismic:
sound waves reflection and refraction from subsurface layers with different characteristics
Gravity Anomalies
Gravity

- craters are relatively shallow features, but depressions
- associated to brecciation and fracturing, extending to significant depth below the crater floor
- fractured rock is less dense than unaltered rock material
- dependent size and morphology, density contrast and burial depth

→ circular negative gravity anomaly
Gravity anomaly: Simple crater

- Negative; unless filled or eroded
Gravity anomaly: Complex Crater

- fracturing and brecciation of target rock and minerals
- formation of high-pressure polymorphs
- mineralogic diaplectic change
- uplift of the rim wall
- formation of allochtonous breccia and melt sheets
# Density Contrast

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Density (kg/m³)</th>
<th>Distance (km)</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gosses Bluff, Australia</td>
<td>Sedimentary</td>
<td>150</td>
<td>22</td>
<td>142.5 ± 0.5</td>
</tr>
<tr>
<td>Mjølnir, Norway</td>
<td>Sedimentary</td>
<td>150</td>
<td>40 (25)</td>
<td>142 ± 6</td>
</tr>
<tr>
<td>Brent, Canada</td>
<td>Crystalline</td>
<td>170 - 340</td>
<td>3.8</td>
<td>450 ± 30</td>
</tr>
<tr>
<td>Nicholson Lake, Canada</td>
<td>Crystalline</td>
<td>70 – 140</td>
<td>12.5</td>
<td>~400</td>
</tr>
<tr>
<td>Clearwater West, Canada</td>
<td>Crystalline</td>
<td>170</td>
<td>32</td>
<td>290 ± 20</td>
</tr>
<tr>
<td>Holleford, Canada</td>
<td>Crystalline</td>
<td>240</td>
<td>2.35</td>
<td>550 ± 100</td>
</tr>
<tr>
<td>Manicouagan, Canada</td>
<td>Crystalline</td>
<td>130</td>
<td>100</td>
<td>212 ± 1</td>
</tr>
<tr>
<td>Söderfjärden, Finland</td>
<td>Crystalline</td>
<td>160</td>
<td>6</td>
<td>~550</td>
</tr>
<tr>
<td>Average (Crystalline)</td>
<td></td>
<td>177.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pilkington & Grieve 1992
Gravity Signatures

Pilkington & Grieve 1992
Statistics on gravity anomalies

Figure 4. Variation in the maximum negative gravity anomaly with crater diameter. Line marked BAZ shows the variation predicted by the simple hemispherical crater model of Basilevsky et al. [1983].

Pilkington & Grieve 1992
Modelled …

Pilkington & Grieve 1992
Mascon
## Typical Densities

<table>
<thead>
<tr>
<th>Category</th>
<th>Density (Mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unconsolidated</strong></td>
<td></td>
</tr>
<tr>
<td>clay</td>
<td>1.5–2.6*</td>
</tr>
<tr>
<td>sand, dry</td>
<td>1.4–1.65</td>
</tr>
<tr>
<td>sand, saturated</td>
<td>1.9–2.1</td>
</tr>
<tr>
<td><strong>Sediments</strong></td>
<td></td>
</tr>
<tr>
<td>chalk</td>
<td>1.9–2.5</td>
</tr>
<tr>
<td>coal, anthracite</td>
<td>1.3–1.8</td>
</tr>
<tr>
<td>coal, lignite</td>
<td>1.1–1.5</td>
</tr>
<tr>
<td>dolomite</td>
<td>2.3–2.9</td>
</tr>
<tr>
<td>limestone</td>
<td>2.0–2.7</td>
</tr>
<tr>
<td>salt</td>
<td>2.1–2.6</td>
</tr>
<tr>
<td>sandstone</td>
<td>2.0–2.6</td>
</tr>
<tr>
<td>shale</td>
<td>2.0–2.7</td>
</tr>
<tr>
<td><strong>Igneous and metamorphic</strong></td>
<td></td>
</tr>
<tr>
<td>andesite</td>
<td>2.4–2.8</td>
</tr>
<tr>
<td>basalt</td>
<td>2.7–3.0</td>
</tr>
<tr>
<td>gneiss</td>
<td>2.6–3.0</td>
</tr>
<tr>
<td>granite</td>
<td>2.5–2.8</td>
</tr>
<tr>
<td>peridotite</td>
<td>2.8–3.2</td>
</tr>
<tr>
<td>quartzite</td>
<td>2.6–2.7</td>
</tr>
<tr>
<td>slate</td>
<td>2.6–2.8</td>
</tr>
<tr>
<td><strong>Minerals and ores</strong></td>
<td></td>
</tr>
<tr>
<td>barite</td>
<td>4.3–4.7</td>
</tr>
<tr>
<td>chalcopyrite</td>
<td>4.1–4.3</td>
</tr>
<tr>
<td>galena</td>
<td>7.4–7.6</td>
</tr>
<tr>
<td>haematite ore</td>
<td>4.9–5.3</td>
</tr>
<tr>
<td>magnetite ore</td>
<td>4.9–5.3</td>
</tr>
<tr>
<td>pyrite</td>
<td>4.9–5.2</td>
</tr>
<tr>
<td>sphalerite</td>
<td>3.5–4.0</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
</tr>
<tr>
<td>oil</td>
<td>0.6–0.9</td>
</tr>
<tr>
<td>water</td>
<td>1.0–1.05</td>
</tr>
</tbody>
</table>

*The ranges of values (taken from a variety of sources) are approximate. Densities depend partly on whether the rock is weathered and the degree of its porosity.*
Potential fields

**Gravity Field**

\[ g = \frac{GM}{r^2} \]

\[ m = \text{mass} \]

**Magnetic Field**

\[ B = \frac{2m_{\text{mass}} \Omega}{r^3} \]

\[ \Phi = \frac{\text{main } \Phi}{r^2} \]

\[ m = \text{dipole moment} \]
**Gravity – Magnetic Field**

<table>
<thead>
<tr>
<th>Monopolar</th>
<th>Dipolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attractive (+ or -)</td>
<td>Attractive and repulsive (+ AND -)</td>
</tr>
<tr>
<td>1/R² dependency</td>
<td>1/R³ dependency</td>
</tr>
<tr>
<td>Density variations</td>
<td>Variation of magnetic susceptibility</td>
</tr>
<tr>
<td>Reflects a bulk rock property</td>
<td>Reflects presence of trace elements</td>
</tr>
<tr>
<td>Source depth is very non-unique</td>
<td>Source depth within 10-20% accuracy</td>
</tr>
<tr>
<td>Stable</td>
<td>Time dependent</td>
</tr>
</tbody>
</table>
Magnetic Anomalies
Magnetic anomalies

- more complicated than gravity
- no specific signature, but
  - anomalous low or random signature interrupt the regional magnetic pattern (fragmentation and mixing of target rock)
  - strong local magnetic anomaly (melt or uplift)
  - circular
  - if associated to melt, it could be used for palaeomagnetic dating
Seismic Reflection or Refraction

Sound waves (pulses) are sent downward. They are reflected or refracted by layers with different properties in the crust. Different materials have very different sound speeds.
Seismic studies

- refraction and reflection
- reveal subsurface deformation, distinctive for impact structures
  - modest downward and inward displacement of rocks along the edges
  - structural disruption with no coherent seismic reflectors, (roughly corresponding to the transient cavity)
  - presence of reflectors in the central zone at greater depth, is evidence that the structure is shallow and not connected with roots the lower crust or mantle
  - essential when buried under younger sediments or water
Electrical Methods

- resistivity variations due impact related target modification
  - impact induced increased porosity and fluid content (low)
  - uplifted material (high)
  - extends farther than the rim
Global Crater Distribution

http://www.unb.ca/passc/ImpactDatabase/
Chicxulub

filtered magnetic anomalies

Pilkington & Hildebrand 2000
Chicxulub

Bouguer gravity horizontal gradients: highlights lateral density contrasts and suppresses regional anomalies

Cenote distribution

Hildebrand et al. 1995
Chicxulub
Global Crater Distribution

http://www.unb.ca/passo/ImpactDatabase/
Geological / Structural Interpretation
Global Crater Distribution

http://www.unb.ca/passc/ImpactDatabase/
Roter Kamm

27°46'S 16°18'E
2.5 km 5 ± 0.3 Ma
Morphology

- 40 km in diameter
- 8-km wide central uplift, 4-km wide annual trough and a 12-km wide outer zone
  Gudlaugsson, 1993

- apparent depth 30-70 m
  Tsikalas et al. 1998

- Volgian-Ryazanian; 142±6 Ma
  Dypvik et al. 1996; Smelror et al. 2001
Seismics

Bjarmeland Platform:

- horizontally layered sedimentary sequences of Devonian to Jurassic
- pronounced horizontal reflector marking the top of the Permian succession (Barents-Sea wide)
- TopPermian reflector remains undisturbed by the impact

Gudlaugsson, 1993
Tsikalas et al. 1998
Aeromagnetic Survey (BAS06)

Sponsored by Chevron, EniNorge, Norwegian Petroleum Directorate, RWE-Dea Norge and StatoilHydro.
L. Gernigon and J.O. Mogaard collected and processed the survey data.
Core 7329/03-U-01

- close to structure centre, depth 171m
- total susceptibilities: Bartington MS2c sensor in core-scanning set-up
- volume-specific susceptibilities
- range: 0-200 SI10⁻⁵; typical values for marine sedimentary rocks
- peak values found for siderite-cemented beds or nodules
- other sources are detrital magnetic minerals
Gravity
Core 7329/03-U-01

- close to structure centre, depth 171m
- dry bulk densities (most samples dissolve in water)
- range 1500 –2900 kg/m³
- were used to constrain the uppermost layers of the gravity model
Modelling Results

Water:
1030 kg/m³
Unconsolidated Sed.1:
1500 kg/m³
Unconsolidated Sed.2:
1700 kg/m³
Consolidated Layered Sed.:
2150 kg/m³
Breccia:
2350 kg/m³
Shattered Zone:
2450 kg/m³
Ansian to Jurassic Deposits:
2500 kg/m³
Permian Deposits:
2550 kg/m³
Crust:
2670 kg/m³
Global Crater Distribution

http://www.unb.ca/passc/ImpactDatabase/
Gardnos
60°39' N 9°0'E
5 km 500 ± 10 Ma
Gardnos

Gravity and Magnetic Anomaly Maps
Summary

• main attribute: circularity
• useful to describe the structural features
• though no proof for impact origin, good for crater detection
• Gravity: generally negative anomaly
• Magnetics: complex and dependent on the presence of magnetic mineral assemblages
• Seismics: structural information
• Other Methods: general mapping
• Modelling is needed for more information subsurface structures
• Calibration utilising properties measured in drill cores