A proposed explanation of how craters and basins become more shallow with size. Charles J. Byrne, Image Again, charles.byrne@verizon.net.

Introduction: Simple impact craters have a uniform depth to diameter ratio up to a specific size that varies for various target bodies. Beyond that critical size, the features become shallower: the depth to diameter ratio decreases as the diameter increases (see Figure 1).

![Figure 1: The depth to diameter ratio of craters smaller than a certain size is a constant, as predicted by the Maxwell Z-model.](https://example.com/figure1.png)

The average ambient pressure at the depth of the break point is 9.52 kg/ m² with a standard deviation of 1.67 kg/ m². This close similarity of ambient pressures, despite material differences in the crust suggests that the ambient pressure at the depth of an apparent crater or at the maximum depth of streamlines of a transient crater may determine which of two excavation processes will be followed.

Excavation processes: For impact features below the break point, the Maxwell Z Model [Croft, 1980] is a good approximation to the process that creates the transient crater, the rim, and the ejecta field. After the shock wave passes, the ejected material follows streamlines, emerging from the target surface at about 45°.

The equation for a streamline in polar coordinates, centered at the effective origin of the shock wave, is:

\[ R = R_0(1 - \cos(\theta)) \]

where \( R_0 \) is the radius at which the rising streamline passes the depth of the effective origin and \( \theta \) is measured from the vertical axis [Croft, 1980].

Figure 2 shows a streamline normalized on \( R_0 \) The value of Z has been taken as 3 for this figure and the depth of the point of origin of the shock wave is at a normalized value of 0.1.

![Figure 2: The Maxwell Z Model, as modified by Croft for projectiles penetrating the surface, shows ejecta following streamlines that form after the shock wave passes.](https://example.com/figure2.png)

Table 1: Break point parameters

<table>
<thead>
<tr>
<th>Feature</th>
<th>Break Point Diameter (km)</th>
<th>Surface g (m/sec²)</th>
<th>Pressure (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>9.6</td>
<td>2.11</td>
<td>1622</td>
</tr>
<tr>
<td>Mercury</td>
<td>4.8</td>
<td>1.06</td>
<td>3.700</td>
</tr>
<tr>
<td>Mars</td>
<td>3.2</td>
<td>0.70</td>
<td>3.711</td>
</tr>
<tr>
<td>Earth</td>
<td>1.7</td>
<td>0.37</td>
<td>9.780</td>
</tr>
</tbody>
</table>
Further support comes from empirical evidence of lunar craters and basins. When the shape of the target surface is removed, the shapes of lunar apparent craters are self-similar over a wide range of sizes beyond the break point if they are scaled by diameter and depth separately [Byrne, 2007]. Figure 4 shows radial profiles of complex craters that are scaled separately in diameter and depth, showing the property of self-similarity.

References:

Figure 3: This shows the effect on a streamline when the depth exceeds the critical ambient pressure (solid line), forming a complex crater.

Streamlines whose depth exceeds that of the critical ambient pressure would be broken into three segments:
1. the first segment is cool and kinetic, with material moving downward
2. the second segment is hot, where material is driven downward into an area of phase change, carrying momentum that causes turbulence there
3. The third segment is cool and kinetic, rising to the surface as in Figure 1.

The ejected material would be less than that of a simple crater, because it would come only from the third segment. Other than that, the ejection process would follow the same scaling laws of apparent diameter and ejection velocity as for simple craters. However, the depths of the apparent crater, rim, and ejecta field of complex craters would be less than the depth predicted by the Maxwell-Z scaling laws, all by the same ratio.

If a simple rule of a phase change at the critical ambient pressure were absolute, then all complex craters would have the same depth, independent of the apparent diameter. However, the empirical evidence is that this is not so. Depths of complex craters increase with the apparent diameter, but not so rapidly as for simple craters, as shown in Figure 1. A suggested solution is that the penetration depth of the projectile, which increases linearly with its diameter, is the factor that increases the depth of the phase change. For large projectiles, the effective origin of the shock wave would be below the break depth, so the shock wave would be rising at depths below, as well as above, the critical ambient pressure, perhaps encouraging excavation more than phase change.

Supporting evidence: Recent 3-D simulations (Ivanov, 2007, Stewart, 2011) confirm that giant impact features like the South Pole-Aitken Basin produce a cool excavation process and a cylindrical melt column extending to much greater depth.