Crater formation in the transition from circular to elliptical impact structures

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Why are some craters circular and others elliptical? How do elliptical craters form? (How) does the cratering mechanism change with the impact angle?

We address these questions by conducting a comprehensive numerical study. This enables to reveal how elliptical craters form, to identify morphological features of elliptical craters and to deliver new insights into crater formation in general.

Simulation setup

Numerical Code: *iSALE-3D* [1,2]

- gravity g=9.81 m/s^2
- impact angle α=90°... 5°
- impact velocity U=8,12,18 km/s
- projectile diameter L=250 m, 500, 1km, 2.5 km, 4km
- Material: granite (Tillotson EOS)
- material strength varied (Drucker-Prager):
  - cohesion Y_{coh}=0, 5, 20, 100, and 200 MPa
  - friction coefficient f=0., 0.2, 0.3, 0.4, 0.5, 0.7, and 1.0

- *800 3D simulations with a resolution of 16...24 CPPR.*

Results

- Crater shape is the result of two competing cratering mechanisms
  - energy transfer along the projectile trajectory in the early stage of impact cratering ("moving point source")
  - a circular and symmetric energy transfer originating from a point afterwards ("static point source").
- Morphological characteristics of elliptical craters comprise features in downrange generated by the moving projectile
- Fragmentation or decapitation of the projectile might occur and create additional structures

Elliptical crater formation

Transition regime *here: α=20°*

- crater growth similar to moderate oblique impacts (>30°).
- most of the ejected material moves parallel to the target surface
- → **still (nearly) circular crater**

Ricochet regime *here: α=10°*

- projectile hardly penetrates into the target while it undergoes shockwave compression
- crater formation initially driven by momentum transfer from projectile to target → elliptical crater evolves; subsequently, shock-induced symmetric excavation flow superimposes
- → **elliptical, but still relatively deep crater**

Grazing regime *here: α=5°*

- projectile barely penetrates into the target
- only small part of impact energy transferred into target (see [1]) → Low shockwave amplitude
- Strong pressure gradient in projectile suggests fragmentation or even decapitation (see [3,4]).
- → **highly elliptical and shallow crater**

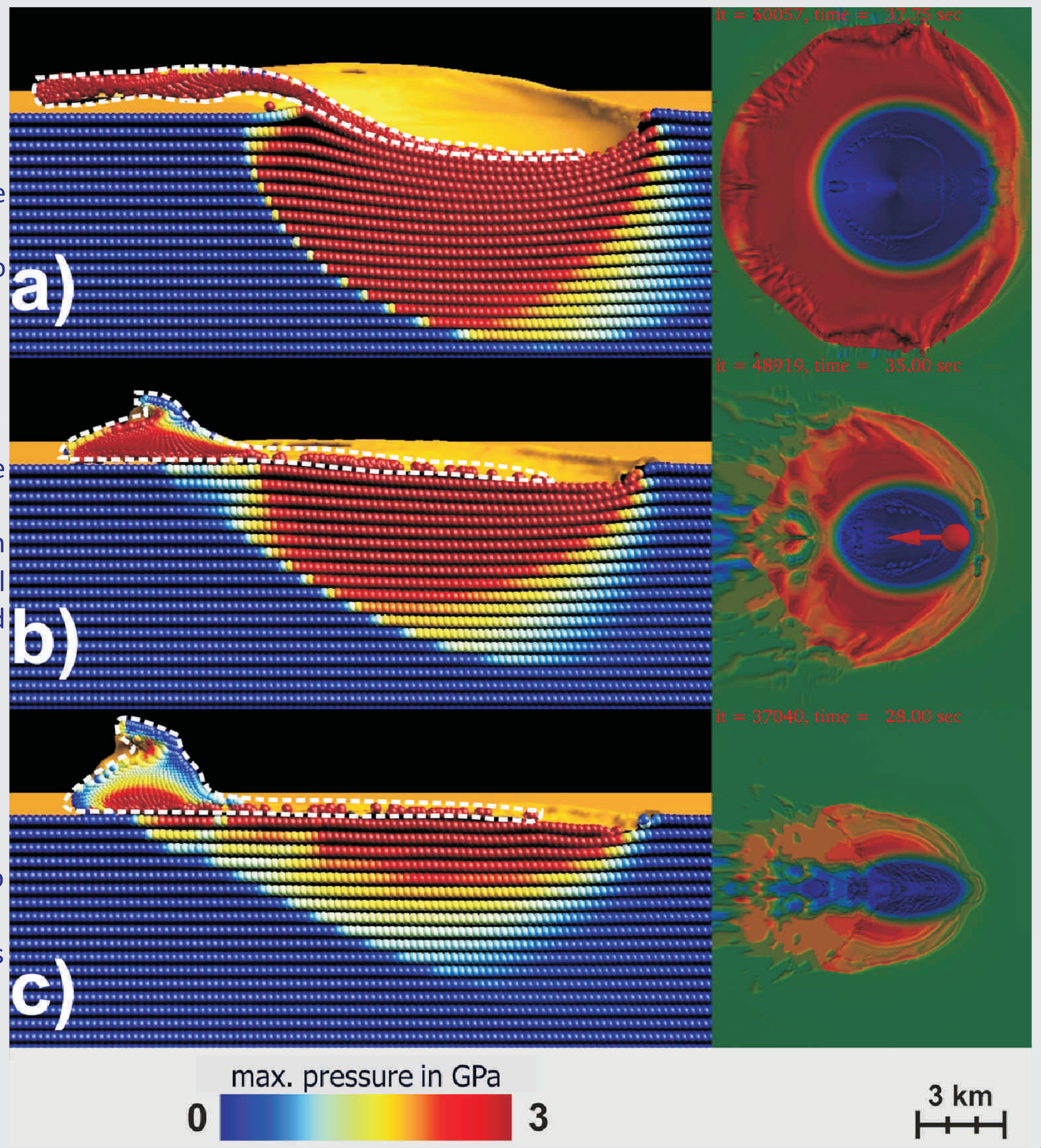
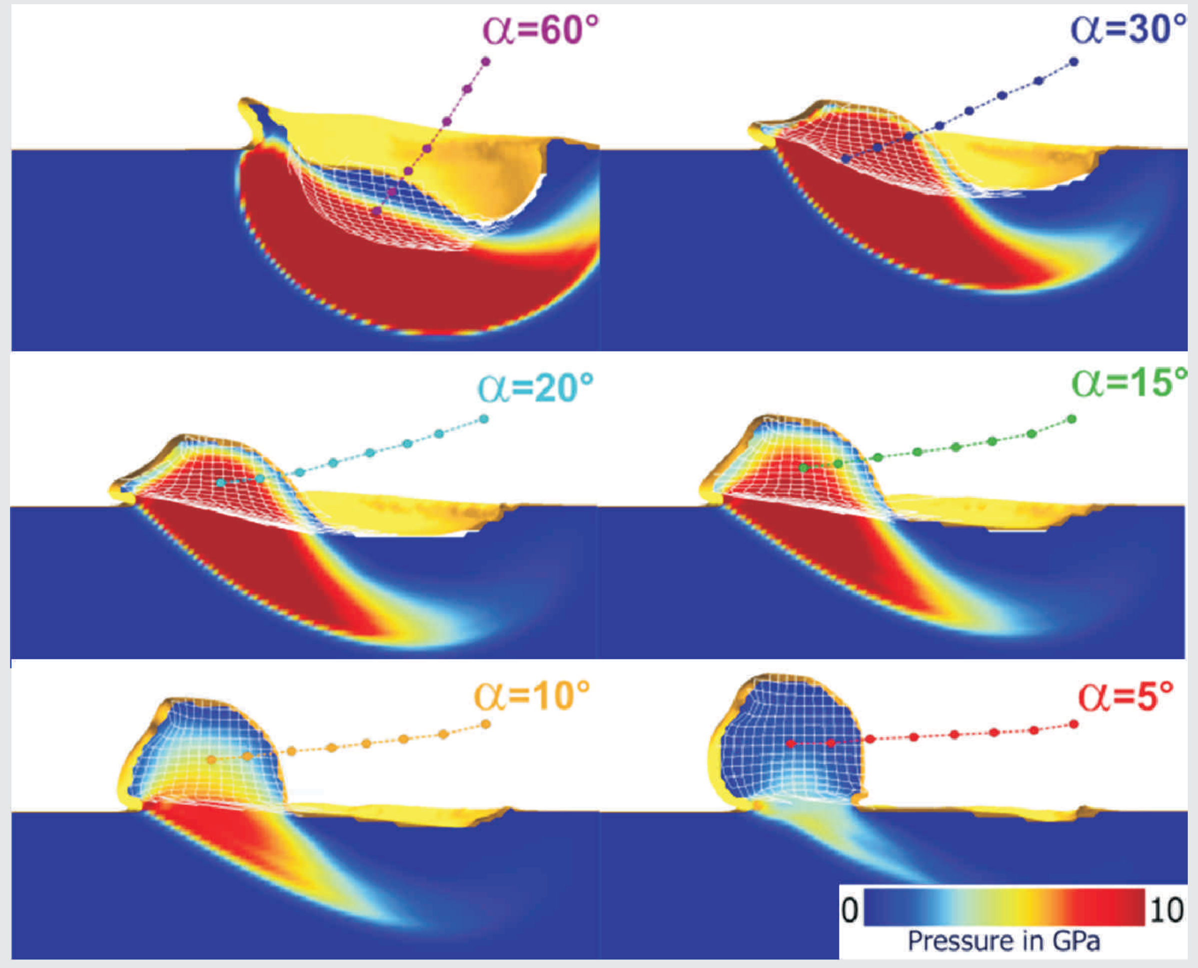


Fig. 1: Crater formation after 4 km size impact at 8 km/s. Y_{coh}=5 MPa, f=0.3.

Projectile motion



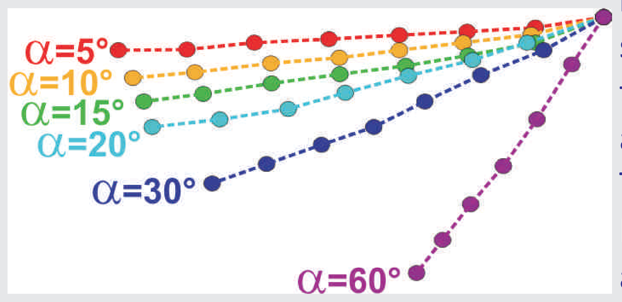
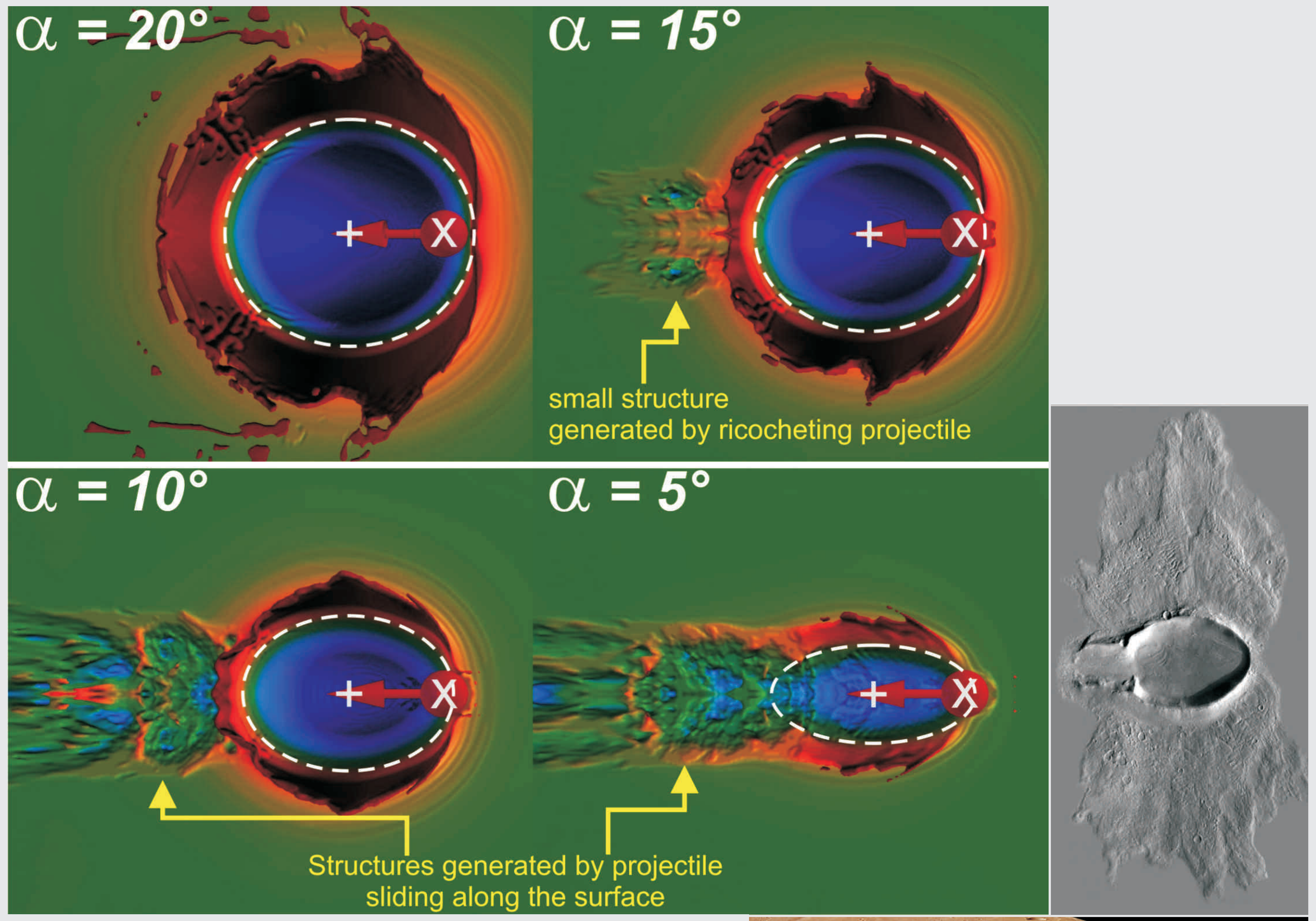


Fig. 3: Projectile motion during early stage of cratering. The points mark the trajectory of the projectile center at various timesteps. Top: Deformation of the projectile. Left: Projectile motion for all impact angles in a direct comparison.

Morphology of elliptical craters



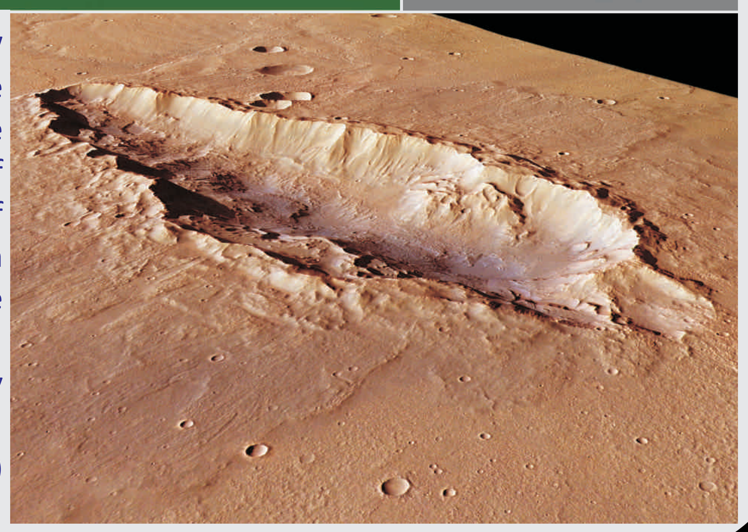


Fig. 2: ***Top left:*** Impact of a 5 km sized projectile at 8 km/s and low impact angles α (friction coefficient f=0.3; no cohesion). The white dashed line marks the inner boundary of the crater cavity before onset of crater modification. The cross (X) marks the contact point of the projectile with the target, the '+' marks the geometric center of the crater. Secondary structures close to the downrange crater rim are the result of the projectile motion along the target surface (friction) and indication for a very oblique impact angle.
Top right: Crater on Mars (ricochet regime; ©NASA/JPL/ASU, Emily Lakdawalla).
Right: Highly elliptical crater (south of Huygens-Crater; 21°S / 55°E) on Mars (grazing regime; ©ESA/DLR/FU-Berlin, G.Neukum)

Transition from circular to elliptical craters

For low impact angles, the horizontal distance between the geometric crater center and the impact point is constant. → Inefficient depth of burial and energy release

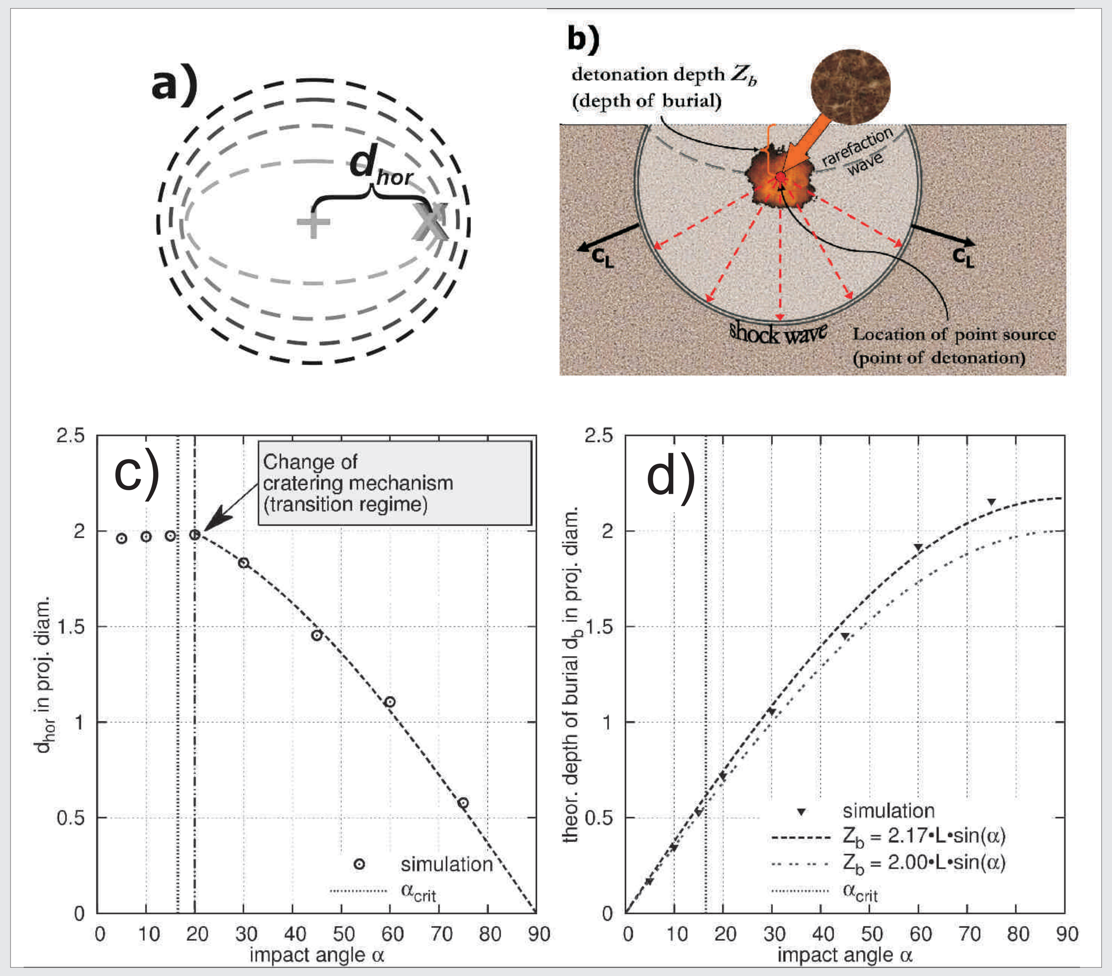


Fig. 4: a) Comparison of crater shapes occurring at different impact angles. The contact point 'X' and the geometric center M_{geom} of the crater '+' are shown, too. Dotted line: crater shape for α=45°, for comparison. **b)** Shockwave propagation after impact. Shock wave propagates with velocity c_L from the detonation center located at depth Z_b. Reflection of the shock wave on free boundaries (here: target surface) initiates rarefaction waves travelling behind the shock. **c)** Distance of the geometric crater center d_{hor} and **d)** depth of burial Z_b as a function of impact angle.

References:
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