MODELING OF THE RHEASILVIA IMPACT CRATER ON VESTA AS BINGHAM PLASTIC FLOW.

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Introduction:
The Dawn spacecraft targeted 4 Vesta, reveal a number ot important details concerning surface morphology, mineralogical composition and internal structure of the dwarf planet [1]. In particular, Dawn has resolved Vesta's south polar feature into two large distinct overlapping impact basins. The largest and youngest of these, Rheasilvia (see Fig. 1a), is centered at 301°W, 75° S, ~15° from the south pole and, at ~500 km in diameter and ~19 km deep [2]. The central massif is a 180-km-wide, 20-to-25-km-high conical dome with well-organized radial and (clockwise) spiral patterns extending from within the central massif out to the basin margin (see Fig. 1b).

Analytical procedure:
Together with geological/geophysical studies and laboratory-scale experiments [3], numerical simulations of impacts contribute a great deal to our knowledge of the large-scale deep structure of impact craters. Based on [4] the best model results are obtained using a "Bingham fluid" strength model [5]. A Bingham fluid has the property of responding elastically to an applied stress until some strength limit, the "Bingham yield stress" is exceeded flowing thereafter as a viscous liquid (see Fig. 2). The slope of a line on the chart is equal to the viscosity in the usual sense.

So, the material is an elastic solid for shear stress τ, less than a critical value τ_0. Once the critical shear stress (or "yield stress") is exceeded, the material flows in such a way that the shear rate, $\partial u/\partial n$ (or velocity's gradient in normal direction, perpendicular to the motion), is directly proportional to the amount by which the applied shear stress exceeds the yield stress:

$$\partial u/\partial n = (\tau - \tau_0)/\mu, \text{ if } \tau \geq \tau_0 \text{ or}$$
$$\partial u/\partial n = 0, \text{ if } \tau < \tau_0 \quad (1)$$

To calculate residual elastic deformations and stresses of Rheasilvia central massif, one can use well developed theory of elasticity for small bodies [6]. The gravitational field strength **F** is determined by the gradient of the approximate gravitational potential

$$\mathbf{F} = \rho_0 \,\mathrm{grad}(GM/\mathbf{r}) \quad (2)$$

ρ_0 is the rock's density, G is the gravitational constant. In the cilindrical coordinate system (the beginning is aligned with the center of the central peak's base, the z axis is vertical), the displacement vector **u** will be presented as the expansion

$$\mathbf{u} = \mathbf{e}_\rho u_\rho + \mathbf{e}_z u_z, \quad (3)$$

where $u_\rho(\rho,z)$, $u_z(\rho,z)$ and $u_\varphi = 0$ are the radial, vertical, and azimuth components of the displacement, respectively.

Then, the equilibrium equation of an isotropic body in the gravitational field takes the form

$$\mu\, \Delta\mathbf{u} + (\lambda + \mu)\, \mathrm{grad}\, (\mathrm{div}\, \mathbf{u}) = -\mathbf{F}, \quad (4)$$

where μ, λ are the Lame constants and

$$\mu = E/2(1+\nu); \ \lambda = \nu E/(1+\nu)(1-2\nu) \quad (5)$$

where ν is the Poisson ratio, and E is the Young modulus of the Vesta's rock.

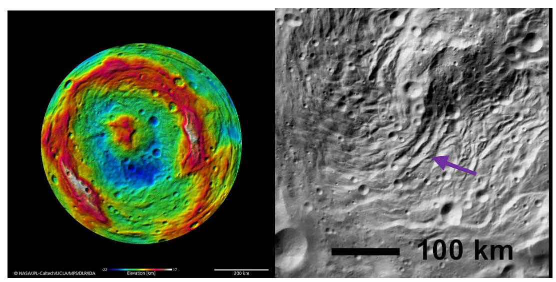

Fig. 1 (a) Vesta's south pole; (b) Spiral deformation patterns within Rheasilvia impact crater.
Image credit: NASA/JPL-Caltech/JAXA/ESA

To analyze the gravitational deformation of a small body, the maximum stress deviator τ_{max} is of the most interest; it is determined by the difference between the maximum σ_1 and minimum σ_3 main stresses:

$$\tau_{max} = (\sigma_1 - \sigma_3)/2 \quad (6)$$

For cone with height h and base radius a, simple "hydrostatic" approximation provides

$$\sigma_{\rho\rho} = \sigma_{\varphi\varphi} = -\sigma_0 (1 - z/h)\, a^2/h^2,$$
$$\sigma_{zz} = -\sigma_0 (1 - z/h), \quad (7)$$

where $\sigma_0 = 1/3\, \rho_0 g_0 h$, $g_0 \approx 0.25$ m/s^2 is the surface gravity. The tension is greatest near the base of the central massif and at the external border is

$$\tau_{max} = ½\, \sigma_0 [1 - (a/h)^2 + (a/h)^4]^{1/2}, \quad (8)$$
$$\sigma_{\rho\rho} = \sigma_{\varphi\varphi} = -\sigma_0 a^2/h^2, \ \sigma_{zz} = -\sigma_0$$

The above discussed simple approximation provides a reasonably accurate estimate of the stresses because of the Vesta's radius, R ≈ 265 km, and the period of rotation, T ≈ 5,34 hours:

$h/R \approx 0{,}094$ and

$(2\pi/T)^2\ h/g_0 \approx 0{,}011$

So, conditions (8) give within 10% error

$\tau_{max} \approx 48$ MPa and $|\sigma_{\rho\rho}| \approx 93$ MPa, (9)

if we take $\rho_0 \approx 3$ g/cm3 as mean density of the Vesta's surface rocks (unbrecciated olivine-rich diogenites).

Results and discussion:

As well known from numerical modeling of the huge impact [7], in the first few minutes crater is formed and central peak is grows to a maximum height. So, the above mentioned spiral deformation patterns within Rheasilvia impact crater could be explained by the action of the Coriolis force on the moving flow of the melt from the central massif out to the basin margin. Rough estimates give velocity of the descending melt as 2-3 km/min or 35-50 m/s and crater's forming time till solidification about 1 hour. It is consistent with the scaling analysis taking into account the diameter of the crater, impact energy, gravity, etc [4]. Such values of velocities were possible if the initial height of the central massif was 6 km more than the current height and was about 30 km.

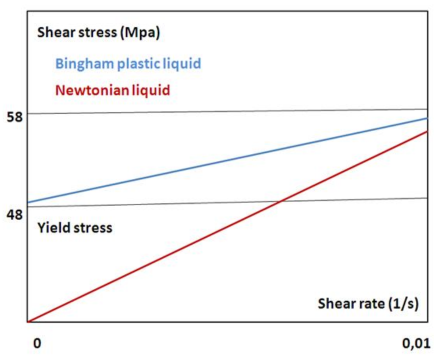

Fig. 2 Bingham plastic flow of Vesta's rock by the Rheasilvia impact event.

So, shear stress calculated be means of (8) for the changing central massif provides the following values of the rock's Bingham plastic flow (see Fig. 2):

τ_0 (yield stress) ≈ 48 MPa;

η (viscosity) $\approx 10^9$ Pa*s.

The mineralogy of Vesta, based on Dawn's spectrosopic data, is consistent with the howardite-eucrite-diogenite (HED) meteorites [8]. South-polar Rheasilvia crater displays a higher diogenitic component. Diogenite are differentiated ultramafic rocks rock composed mainly of magnesium-rich and calcium-poor orthopyroxene. They contain small amounts of olivine and plagioclase and often presents large crystals of pyroxene. It is typical for intrusive rocks formed in a magmatic chambers at the crust of a planet or asteroid and grow under the slow cooling down to an appropriate size. So diogenite are representatives of the magmatic processes that occurred about 4.4 billion years ago with Vesta. Terrestrial analogs of the basalts with similar composition have a compression strength of about 250-300 MPa and it is much more than the compression near the base of the central massif. Perhaps, this is a consequence of the porosity or the presence of cracks at the rocks, which occurred during Rheasilvia basin formation.

A number of HED-meteorites (Dhofar 018, Dhofar 1480 etc.) has been investigated at GEOKHI RAS [9]. It was shown that howardites contain Mg-rich pyroxenite (diogenite) material, basically ejected from Rheasilvia basin where by its central uplift ultramafic rocks were exposed. Also, howardites are the most enriched with noble gases of the solar type and inclusions of carbonaceous and ordinary chondrites. This means that they were exposed long time on the surface of Vesta. Eucrites are composed of calcium-rich plagioclase (anorthite), calcium-poor pyroxene and often contain a certain percentage of nickel. In addition, they often contain cavities, which are hardened gas bubbles and serve as evidence of magmatic origin.

Experimental data on the dependence of viscosity of basalt melts from the SiO_2 content and temperature gives an average temperature T ≈ 830 K for the $\eta \approx 10^9$ Pa*s. Terrestrial analog of the similar basalt melts has initial temperature about 1200-1400 K and lower viscosity. But, surface temperature on Vesta is between min. 85 K and max. 255 K with mass about $2{,}6 \cdot 10^{20}$ kg, only. So, rapid cooling was supposed to accompany the formation of the crater and central massif of Rheasilvia. From the other side, the presence of calcium containing rocks could play a significant role in lowering melt's viscosity and thereby accelerate the formation of the Rheasilvia basin.

References:

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