EARLY VISCOUS RELAXATION OF ASTEROID VESTA AND IMPLICATIONS FOR LATE IMPACT-DRIVEN DESPINNING.

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Introduction: Differentiated asteroids in the present-day solar system represent a relic population of the earliest forming planetesimals. Vesta (mean diameter ~525 km) is the best studied example of a differentiated asteroid. Geochemical evidence from the HED meteorites, which are likely to originate from Vesta, and recent remote sensing data from the NASA Dawn mission indicate that Vesta's surface consists of igneous material and that it contains a metallic core with radius ≈110 km [e.g., 1, 2, 3].

Despite this ample evidence for widespread interior and surface melting in the distant past, present day Vesta, similar to all asteroids except for Ceres, exhibits global scale, non-hydrostatic topography. Orbital mapping of the Vestan surface has revealed the presence of two large (>400 km diameter) relatively unrelaxed impact basins in the southern hemisphere [4, 5]. Furthermore, the current rotation rate of Vesta corresponds to an equilibrium figure with flattening factor f_{eq}=0.128, where f is defined as $(a-c)/a$ with a and c representing the equatorial and polar radii. Meanwhile, the observed best-fit rotational ellipsoid shows greater oblateness with f~0.21 [3].

Unrelaxed global topography on Vesta is consistent with its weak surface gravity and low interior temperatures. Assuming a cool interior, Vesta experiences internal shear stresses on the order of ~1 MPa, which is insufficient to cause pervasive brittle failure. At the same time, viscous relaxation on cold asteroid-sized bodies requires much longer than the lifetime of the solar system [6].

However, given the high degree of past melting in Vesta, augmented shear stresses in a thin, chilled lithosphere may have caused deformation via brittle failure during the asteroid's early history. Likewise, elevated interior temperatures may have allowed for viscous relaxation of global topography on geologically short timescales. As such, Vesta may have reached hydrostatic equilibrium during a brief early epoch.

Topography on Vesta may therefore consist of a mixture of ancient terrains that achieved hydrostatic equilibrium during an early period of intense heating and late non-hydrostatic features acquired after Vesta cooled sufficiently to prevent further relaxation.

We use finite element models to evaluate the potential for hydrostatic relaxation on early Vesta and thereby assess the possibility that hydrostatic terrains exist on present day Vesta. We identify a large region in the northern hemisphere of Vesta as a likely manifestation of such relic hydrostatic terrain and use its morphology to constrain the extent of late despinning and reorientation.

Model description: We simulate the viscous relaxation of Vesta using the deal.II finite element library [7]. We solve the Stokes equations on a 2D, axisymmetric mesh with up to ~6000 cells. Because we are interested in the relaxation of topography at the longest wavelengths, we adopt ellipsoids of rotation for our shape models. The relaxation model is run for a range of ages and non-hydrostaticity with f-f_{eq} ranging up to the present day value of 0.082, which represents 9 km of disequilibrium topography at the equator.

To constrain the initial temperature profile for a viscous flow simulation at a given age, we construct a simple, 1D conductive cooling model that accounts for heating from long-lived radiogenic isotopes and the insulating effect of a megaregolith layer. The thickness of megaregolith on present day Vesta may be greater than 5 km [8]. However, megaregolith thickness for early Vesta depends on the frequency of large impacts during early history and is therefore uncertain. We adopt 0 km and 5 km as lower and upper bounds for megaregolith thickness in our cooling model.

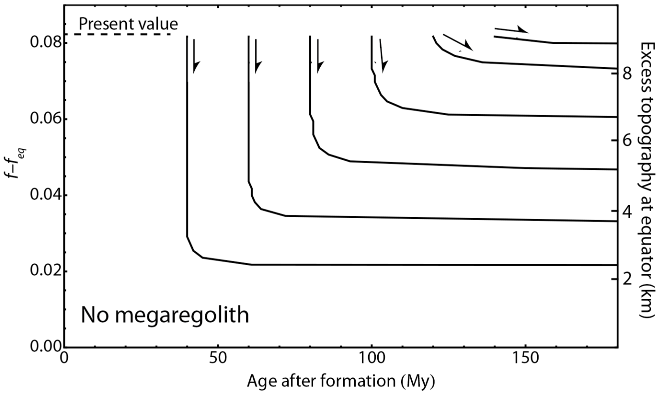

Fig. 1. Projected paths of viscous relaxation. Vesta was able to relax to more hydrostatic figures during its earliest history. The observed present day disequilibrium (f-f_{eq}= 0.082) was only possible after ~4.43 Ga (~120 My after formation).

Efficient early viscous relaxation: The rate of viscous relaxation varies approximately exponentially with both the degree of disequilibrium and age. Faster relaxation occurs in early Vesta due to higher interior temperatures and therefore exponentially lower viscosities. At the same time, higher lithospheric stresses due to more non-hydrostatic figures lead to more extensive brittle failure and faster relaxation.

Vesta reached a much higher degree of hydrostatic equilibrium than its present figure during its early history (Fig. 1). In the case of no megaregolith, Vesta achieved and maintained a hydrostatic figure with f-f_{eq} less than 0.02 (≈2 km equatorial bulge amplitude) during the first ~30 My years after formation. The present degree of non-hydrostaticity was sustainable only after ~4.43 Ga.

The presence of thick megaregolith has a strong effect on the rate of viscous relaxation. In the endmember case of a 5 km megaregolith layer, Vesta was able to maintain f-f_{eq} <0.02 during before ~4.3 Ga. The present equatorial bulge was not possible until after ~4.0 Ga.

The unrelaxed nature of the observed Veneneia and Rheasilvia giant impact basins therefore imply that they were acquired later in Vesta's history. Depending on the megaregolith thickness, ~4.43-4.0 Ga represents an upper bound for their age. Such a late formation is consistent with crater density ages for these impact basins [5].

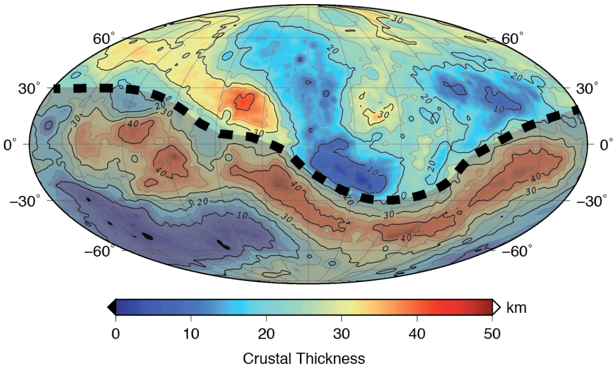

Fig. 2. The undisturbed terrains (north of dashed curve) used in our fit for the hydrostatic figure of early Vesta. These terrains show high crater density and likely escaped significant late reshaping.

Relic hydrostatic terrains on Vesta: Our viscous relaxation models suggest that Vesta achieved a closely hydrostatic figure early in its history. Although Vesta was subject to two late giant impact events, terrains far from these impact basins may have remained largely undisturbed until the present day and may reflect the figure of Vesta's early hydrostatic surface.

The northern hemisphere of Vesta shows high crater densities. Some regions (the HCTs or heavily cratered terrains) are at or near crater saturation [4]. Furthermore, unsaturated regions adjacent to the HCTs exhibit few craters larger than ~50 km, suggesting that they may still faithfully preserve ancient long wavelength topography.

At the same time, giant impact simulations suggest that ejecta from the Rheasilvia basin forming event created a belt of increased crustal thickness near the present day equator. Surface topography beyond this equatorial belt likely underwent minimal modification [e.g., 9].

Crustal thickness maps derived from Bouguer gravity anomalies show a clear ring of high crustal thickness in the equatorial region [10]. The terrain to the north of this belt may therefore represent the relic hydrostatic surface from Vesta's early history. By isolating this region (Fig. 2), we find that the best-fit ellipsoid of rotation has equatorial and polar radii of 278 and 267 km. The volume of this best-fit rotational ellipsoid is 2% larger than that of the present shape, which is fully consistent with the expected volume of ancient Vesta before the effect of the more recent giant impacts [5]. These results are robust with respect to variations in the regions chosen for the fit.

The figure of the best-fit rotational ellipsoid has a flattening of f=0.148, which is greater than that of the equilibrium figure for the present day rotation period and corresponds to a paleo-rotation period of 5.02 hr. The symmetry axis of the fitted ellipsoid of rotation is offset by 4.5° from the modern rotational axis.

Conclusions: We conduct finite element simulations of the viscous relaxation of Vesta during early periods of extensive interior heating. Vesta reached and maintained significantly higher degrees of hydrostatic relaxation than the present day figure during the first 0.1 to 0.5 Gy after formation, depending on the assumed depth of megaregolith.

These viscous relaxation results raise the possibility that hydrostatic terrains from early Vesta are present on the surface of the asteroid today. Ancient and largely undisturbed northern hemisphere terrains of Vesta are consistent with an ancient hydrostatic surface and suggest that the late giant impacts caused a 6% slow-down in Vesta's rotation rate and a reorientation of ~4.5°.

Other differentiated asteroids that experienced similar intense early heating and rapid cooling may have also reached high levels of hydrostatic relaxation during their early history. Observations of relic hydrostatic terrains on asteroids can therefore constrain the extent of early heating.

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