Icarus 240 (2014) 133–145

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Efficient early global relaxation of asteroid Vesta

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ARTICLE INFO

Article history:
Available online 4 February 2014

Keywords:
Asteroid Vesta
Asteroids
Geophysics
Interiors
Planetesimals

ABSTRACT

The asteroid Vesta is a differentiated planetesimal from the accretion phase of Solar System formation. Although its present-day shape is dominated by a non-hydrostatic fossil equatorial bulge and two large, mostly unrelaxed impact basins, Vesta may have been able to approach hydrostatic equilibrium during a brief early period of intense interior heating. We use a finite element viscoplastic flow model coupled to a 1D conductive cooling model to calculate the expected rate of relaxation throughout Vesta's early history. We find that, given sufficient non-hydrostaticity, the early elastic lithosphere of Vesta experienced extensive brittle failure due to self-gravity, thereby allowing relaxation to a more hydrostatic figure. Soon after its accretion, Vesta reached a closely hydrostatic figure with <2 km non-hydrostatic topography at degree-2, which, once scaled, is similar to the maximum disequilibrium of the hydrostatic asteroid Ceres. Vesta was able to support the modern observed amplitude of non-hydrostatic topography only >40–200 My after formation, depending on the assumed depth of megaregolith. The Veneneia and Rheasilvia giant impacts, which generated most non-hydrostatic topography, must have therefore occurred >40–200 My after formation. Based on crater retention ages, topography, and relation to known impact generated features, we identify a large region in the northern hemisphere that likely represents relic hydrostatic terrain from early Vesta. The long-wavelength figure of this terrain suggests that, before the two late giant impacts, Vesta had a rotation period of 5.02 h (6.3% faster than present) while its spin axis was offset by 3.0° from that of the present. The evolution of Vesta's figure shows that the hydrostaticity of small bodies depends strongly on its age and specific impact history and that a single body may embody both hydrostatic and non-hydrostatic terrains and epochs.

1. Introduction

The terrestrial planets likely formed via the successive accretion of tens to hundreds of kilometer diameter objects known as planetesimals (Chambers, 2004). The high abundance of short-lived radiogenic isotopes such as ^{26}Al in the early Solar System led to the extensive interior melting of early-forming planetesimals. Thermal evolution models of planetesimals show that bodies as small as 20 km in diameter may have achieved >50% melting if accretion occurred sufficiently early (Hevey and Sanders, 2006; Elkins-Tanton et al., 2011; Šrámek et al., 2011). Such high degrees of melting led to full or partial differentiation of these bodies (McCoy et al., 2006).

Differentiated asteroids in the present-day Solar System represent a relic population of these early-formed planetesimals. Vesta (mean diameter ~525 km) is the best studied example of a differentiated asteroid. Ground-based spectroscopic studies have previously associated the surface of Vesta with meteorites of the howardite–eucrite–diogenite (HED) clan, whose geochemistries indicate igneous origins on a fully differentiated body (McCord et al., 1970; Binzel and Xu, 1993; Righter and Drake, 1997). More recently, the NASA Dawn mission, in orbit around Vesta between July 2011 and September 2012, deduced the presence of a metallic core with radius 110 ± 3 km when assuming a core density similar to that of iron meteorites and measured surface spectra consistent with the HED meteorites (Russell et al., 2012; De Sanctis et al., 2012; Reddy et al., 2012).

Despite evidence for past interior and surface melting, 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) and relatively unrelaxed impact basins in the southern hemisphere (Marchi et al., 2012; Schenk et al., 2012). Furthermore, assuming a core and mantle with uniform densities, the current rotation rate of Vesta corresponds to a hydrostatic shape with flattening factor $f_{eq} = 0.13$ (see Section 3.1). The flattening factor f is defined as

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http://dx.doi.org/10.1016/j.icarus.2014.01.023
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$(a-c)/a$ where a and c are the equatorial and polar radii of the best-fit ellipsoid of revolution.

In contrast, the observed best-fit ellipsoid shows greater oblateness, with $f \approx 0.19$ (Konopliv et al., 2014). This equatorial bulge of Vesta represents a non-hydrostatic fossil bulge; it cannot be explained by compensated topography as thickened, isostatically relaxed crust is expected to show a negative Bouguer anomaly. However, no such feature is observed at degree-2 (Ermakov et al., 2014). The corresponding global disequilibrium factor $(f - f_{eq})$ of 0.07 is more than three orders of magnitude greater than the value for the Earth (Chambat et al., 2010). The impact basins and the non-hydrostatic bulge may have formed in the same giant impact events, which may contribute to topographic disequilibrium via direct redistribution of mass and change to the rotation period or axis.

Unrelaxed global topography on Vesta and other asteroids is consistent with their low surface gravity and the high strength of cold silicates. Assuming a cool interior, large asteroids such as Vesta experience internal shear stresses on the order of ~1 MPa due to disequilibrium topography and spin axis reorientation (Johnson and McGetchin, 1973; Matsuyama and Nimmo, 2011), which is insufficient to cause pervasive brittle failure even in previously fractured basaltic masses (Schultz, 1993). At the same time, viscous relaxation on asteroid-sized bodies with ambient temperatures of the present-day asteroid belt is expected to require much longer than the age of the Solar System (Johnson and McGetchin, 1973).

However, given the high degree of past melting in differentiated asteroids such as Vesta, high shear stresses in a thin, chilled surface layer may have led to pervasive brittle failure and associated deformation during Vesta's early history. Likewise, the elevated temperatures may have allowed for viscous relaxation of topography on geologically short timescales.

Relaxation may have occurred on Vesta under two distinct scenarios (Fig. 1). In Relaxation Scenario One, Vesta may have relaxed from a non-hydrostatic shape in which it initially accreted. Although it is unclear whether Vesta and other planetesimals formed via large instabilities or incremental growth (Morbidelli et al., 2009; Weidenschilling, 2011), no accretion mechanism predicts formation in an already hydrostatic figure. As such, Vesta very likely accreted in a non-hydrostatic shape. Meanwhile, energy from the accretion process was likely insufficient to melt Vesta (Poitrasson et al., 2004; Šrámek et al., 2011). Vesta was therefore at first unable to relax from the non-hydrostatic figure in which it accreted. Short-lived radioactive isotopes subsequently heated the Vestan interior, leading to differentiation and a thin lithosphere on the order of one to several million years (Ghosh and McSween, 1998; Tang and Dauphas, 2012). Relaxation from the originally accreted shape to a closely hydrostatic one may have occurred at this time.

After the initial relaxation, large early impacts may have led to Relaxation Scenario Two. Such large impacts may have recreated significant non-hydrostatic topography during a brief early window; there is a 12–31% probability that Vesta was struck by a Rheasilvia basin-forming impactor sized object during the first 100 My (Davison et al., 2013). Because the cooling of the Vestan interior occurred gradually (see Section 2.2), Vesta would have been able to return to a closely hydrostatic figure if a large impact occurred sufficiently early. This relaxation may obscure the long wavelength topography introduced by such early impacts, although the lack of compositionally distinct regions on the surface of Vesta excavated by such purported impacts suggests that they did not occur or that they occurred while igneous resurfacing on Vesta was still ongoing. As the interior of Vesta cooled, hydrostatic relaxation would have become impossible during its later history.

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. Crater retention ages derived from Dawn observations show that the surface of Vesta indeed consists of both old and young terrains. The two large impact basins in Vesta's southern hemisphere are young features that have model ages of 2.1 ± 0.2 (for the Veneneia basin) and 1.0 ± 0.2 (Rheasilvia basin) Ga (Schenk et al., 2012). Meanwhile, the northern hemisphere of Vesta may have reached crater saturation and likely has not experienced catastrophic reshaping since early in Vesta's history (Marchi et al., 2012).

In this study, 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. As described in Section 2, we construct numerical viscoplastic deformation models using the deal.II finite element library (Bangerth et al., 2007). The flow model is coupled to a simple secular cooling model for Vesta that accounts for the effects of radiogenic heating and an insulating megaregolith layer.

In Section 3, we report the expected extent of hydrostatic relaxation as a function of Vesta's age and assumed megaregolith thickness. We find that the global figure of early Vesta was much closer to hydrostatic equilibrium than observed today. We identify a large region in the northern hemisphere of Vesta as a likely relic of this

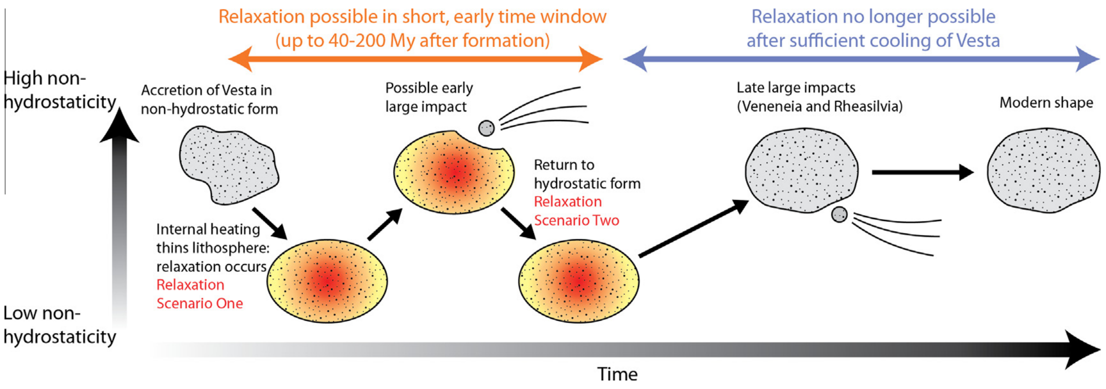

Fig. 1. Schematic illustration of the evolution of Vesta's long wavelength topography. Upon formation, rapid internal heating (denoted by red-yellow coloration) due to short-lived radiogenic isotopes lead to a differentiated interior with a thin, cold lithosphere. Vesta therefore reached a highly hydrostatic figure with a non-hydrostatic equatorial bulge amplitude of <2 km (see Section 3.1). If early large impacts disturbed the figure of Vesta, subsequent relaxation would restore a high hydrostaticity. By 40–200 My after formation, the Vestan interior had cooled sufficiently to prevent relaxation to a figure more hydrostatic than that of the present day. The late Veneneia and Rheasilvia basin-forming impacts occurred after this transition, thereby imparting a significant non-hydrostatic component to Vesta's observed figure.