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Tectonism and Magmatism on Asteroids

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Abstract

Linear features generally accepted as tectonic structures have been observed on several asteroids and their presence has implications for the internal structure, strength and evolution of these various bodies. Observations of several small bodies have identified different physical mechanisms by which linear features can be formed. Analysis shows that asteroid lineaments appear to have different origins. We also discuss the potential for volcanism and/or magmatism on asteroids, especially in regard to Vesta which, as a differentiated proto-planet, is a unique body with which to study the role that internal rheologies and structures play on surface features.

1. Introduction

We present a review of the solar system asteroids that have been visited by spacecraft—951 Gaspra, 243 Ida, 253 Mathilde, 433 Eros, 25143 Itokawa, 2867 Steins, 5535 Annefrank, 21 Lutetia and 4 Vesta—and discuss how analyses of linear structures observed on these small terrestrial bodies have implications for the tectonics of asteroids, models of linear structure formation, and the internal structure of the asteroids. Understanding the tectonic histories of these small rocky bodies provides insights into the dynamics of early solar system formation as well as understanding of the role of endogenic versus exogenic processes in tectonic styles of deformation. We also review Vesta as a unique planetoid in our solar system, in that a geomorphic evaluation suggests that the geological history of Vesta may have included magmatism.

2. Tectonism on Asteroids

Decades ago, linear structural features (grooves) were identified on the Martian moon Phobos in Viking orbiter imagery and interpreted to be the likely result of the large impact that formed Stickney crater [1]. Thus, the majority of the grooves are associated with an exogenic process.

The subsequent imaging of a variety of asteroids led to new models being proposed for the formation of asteroid lineaments that include both exogenic and endogenic processes. These formation models include: 1) formation by impact [2,3], 2) fabric inherited from a parent body [4], 3) down-slope scouring [5,6,7], and 4) thermal stresses [8].

Asteroid lineaments observed appear to have several different origins, and are indicative of variable interior structures. Many of the linear structures, such as those on Ida, Eros, Lutetia and Vesta, appear to be due to impact, but some lineaments have no obvious relationship to impact craters. For example, some of the linear structures on Gaspra and Eros are indicative of a fabric in a coherent asteroid inherited from a parent body, and are consistent with previous suggestions that Gaspra and Eros are fragments of larger parent bodies [9,10]. Pervasive subsurface fracturing can also be distinguished by the polygonal shapes of some craters on Mathilde [11], Eros [12,13] and Lutetia [14]. The presence of long structural features on the surfaces of some asteroids is indicative of substantial internal strength, despite low-density values that indicate high porosity. Meanwhile, lineaments on Itokawa have been associated with boulders and are consistent with the excavation of regolith by boulder movement on a "rubble pile" asteroid [7]. Vesta presents an intermediate style of tectonic deformation, with fractures and grooves similar to those observed on other asteroids, as well as large-scale graben and trough structures more characteristic of tectonics on terrestrial planet [15]. However, unlike the terrestrial planets Vesta's main stressors have been primarily exogenic (i.e. impacts) rather than internally driven [15, 16]. It is therefore clear that determining how linear features formed on these asteroids yields important information about their internal structure and strength, as well as on its nature and history.

3. Magmatism on Asteroids

Although none of the other asteroids that have been visited to date were expected to show signs of volcanism and/or magmatism, it has long been suspected that Vesta may have undergone volcanic and/or magmatic activity at some point in its history [e.g. 17, 18]. Spectroscopic studies of Vesta [e.g. 19, 20] show that it has similar spectral signatures to the howardite–eucrite–diogenite (HED) meteorites [e.g. 21-24]. This similarity indicates that the HEDs may be vestan fragments [e.g. 22, 25]. Since the HEDs are all igneous in nature, this in turn suggests that Vesta might have experienced volcanism or magmatism.

Hypotheses of igneous intrusion on Vesta suggested that dikes could occur on Vesta, based on mathematical and petrological modeling [17]; these models indicated that both shallow and deep dikes were possible. A detailed study of the trace-element chemistry of diogenites suggests that they possibly formed as later-stage plutons injected into the eucritic vestan crust [27]. There may also be many sill-like intrusions at the base of Vesta's lithosphere [28].

The search for volcanic and magmatic features was thus a primary focus of the Dawn mission at Vesta. A comprehensive evaluation of lobate flows on Vesta yielded no unequivocal morphologic evidence of ancient volcanic activity [26]. However, some indication of magmatic processes has been identified [16]. A synthesis of tectonic, geomorphic and compositional analyses of the elongate hill Brumalia Tholus suggests that it formed as molten material utilized a subsurface fault as a conduit to travel towards Vesta's surface, intruding into and deforming the rock above it [16].

4. Summary

As a group, asteroids represent some of the earliest remnants of the early solar system. Deciphering the tectonic histories of these bodies provides insight into the complex dynamical and geological history of the inner solar system. Although currently limited by available observations, our understanding of asteroid composition and structure has grown exponentially in the last few decades, leading to improved recognition and classification of asteroid characteristics based on strength and cohesion. Impact processes dominate the tectonic styles observed on many asteroids, but there is also evidence for structure inherited from parent bodies. Vesta represents a transitional form of tectonics that reflects its internal differentiation and impact history, and observations suggest that its geologic history may have included endogenic magmatism.

As we study the icy dwarf planets of Ceres and Pluto, a better understanding the styles of tectonism, and the endogenic versus exogenic processes involved on these smaller bodies will aid in the interpretation of tectonism and volcanism on all solid bodies in the solar system.

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