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Fault geometries on Uranus' satellite Miranda: Implications for internal structure and heat flow

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ABSTRACT

Miranda, a ~470-km-diameter uranian icy satellite, has a surface that exhibits evidence of a complex tectonic history. Tectonic structures are mostly localized in three regions termed coronae, but also form a rift system inferred to be global in extent. Ridges within the boundary of Arden Corona, and those that make up the 340° Chasma, part of the global rift system, have been interpreted as normal fault blocks. Using Voyager data, we test the hypothesis that these Arden Corona faults, as well as those at the northern edge of the 340° Chasma, are listric in geometry. For this testing, we use four geometric criteria for listric faults: (1) progressive down-dip decrease in fault scarp dip, (2) progressive down-dip increase in back-tilted face slope, (3) concavity of the exposed scarp surface, and (4) presence of a rollover structure. Results of this analysis support the hypothesis that the faults within the Arden Corona boundary are listric in geometry, but do not strongly support the hypothesis for the faults within the 340° Chasma. By analogy with terrestrial structures, the listric character of faults within the Arden Corona boundary suggests the presence of a subsurface detachment. This detachment likely occurred at Miranda's brittle–ductile transition zone at the time of faulting. Measurements of the Arden Corona fault system geometry are used to estimate depths to the proposed brittle–ductile transition zone at the time of faulting, resulting in values of 6.7–9.0 km. Those depths in turn are used to estimate a thermal gradient of 6–25 K km^{-1} and a surface heat flux of 31–112 mW m^{-2}. The weaker evidence of a listric geometry for the faults of the 340° Chasma suggests that those faults did not interact with a brittle–ductile transition at the time of their formation. Our estimated thermal gradient of the Arden Corona region is consistent with a previous heating event on Miranda that was as significant as Europa's current resonance-induced tidal heating. This heating event may be associated with a hypothesized previous tidal resonance of Miranda with Umbriel and/or Ariel.

1. Introduction

Miranda, a small (~470-km-mean-diameter) icy satellite, is the innermost of the five major uranian satellites. Like the other major icy satellites of Uranus, Miranda displays lineaments inferred to have resulted from regional or global rifting. Unlike any other satellite in the uranian system, Miranda exhibits enigmatic features known as coronae (Fig. 1). Coronae are characterized by ovoid or trapezoidal shapes in plan view, and are separated from the surrounding cratered terrain by a series of subparallel linear features that make up the coronae boundaries. These linear features are diverse in albedo and have been interpreted as ridges and troughs (Smith et al., 1986). Coronae interiors consist of smoother terrains and/or additional topographic linear features. Within Arden and Inverness Coronae, albedo contrasts highlight individual ridges and troughs, where the darker linear features correspond to outward facing ridge walls that exist within the coronae and the higher albedo linear features correspond to ridges (Smith et al., 1986; Pappalardo et al., 1997). In contrast, the ridges and troughs of Elsinore Corona appear to have a more uniform albedo (Figs. 1 and 2).

Previous work indicates that Miranda's coronae are at least partially tectonic in origin (Thomas, 1988a; Greenberg et al., 1991; Schenk, 1991; Pappalardo, 1994; Pappalardo et al., 1997). Specifically, sloping surfaces have been inferred to be normal fault scarps based on multiple lines of evidence, including the presence of slope lineations that trend perpendicular to the ridges (Pappalardo et al., 1997). Although some of these lineations may be associated with mass wasting (see Pappalardo et al. (1997) for a summary of evidence for mass wasting on Miranda), most are instead inferred to be corrugations caused by the relative downward movement of the hanging walls along the scarps. Evidence supporting this interpretation includes consistent widths from the top to bottom of the

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slopes and the observation that lineations are only present on slopes that face away from the interior of Arden.

The parallel ridges and troughs within the Arden Corona boundary are interpreted as tilted normal fault blocks that may have been partially modified by mass wasting activity (Thomas, 1988a; Greenberg et al., 1991; Schenk, 1991; Pappalardo, 1994; Pappalardo et al., 1997). Three fault scarp dip measurements taken on separate faults by Pappalardo et al. (1997) along the limb of Miranda indicated a decrease in dip away from the interior of Arden Corona. On this basis, these authors suggested that this fault system might be listric in geometry.

As summarized in previous work (e.g. Croft and Soderblom, 1991), several fresh and mantled fault scarps make up a system of rifts. The section of the rift system that trends roughly 340° is termed the 340° Chasma (Croft and Soderblom, 1991) (Figs. 1 and 2). The 340° Chasma transects the southern hemisphere of Miranda, between Inverness and Arden Coronae, and trends subparallel to the Arden-facing boundary of Inverness Corona (Figs. 1 and 2). The faults forming the northern boundary of the 340° Chasma have been interpreted as a graben system, based on the sets of inward-facing slopes that make up the Chasma (Croft and Soderblom, 1991).

Here, we investigate the hypothesis derived from previous work (Pappalardo et al., 1997) that the normal faults within the boundary of Arden Corona are listric in geometry. Given the availability of stereo images over the 340° Chasma, we investigate the additional hypothesis that the normal fault scarps within the 340° Chasma are also listric in geometry. Our alternative hypotheses are that the Arden Corona boundary fault system and the 340° Chasma fault system are planar in geometry.

For listric faults on Earth, measurements of fault geometry may be used to estimate the depth to a detachment (Gibbs, 1983; Williams and Vann, 1987; Poblet and Bulnes, 2005). A detachment may develop along a brittle–ductile transition zone at depth (Shelton, 1984; Ord and Hobbs, 1989; Regenauer-Lieb et al., 2004), which has been commonly inferred for icy bodies (e.g. Ruiz, 2005). If the faults on Miranda are listric and the detachment of the faults correlate with a brittle–ductile transition zone, the fault geometry measurements can be used to estimate the depth to this zone. An estimate of this depth provides information on Miranda's thermal gradient and heat flux around the coronae perimeters during faulting.

2. Background

2.1. Miranda's coronae and global rift system

Only the southern hemisphere of Miranda, which was facing the Sun at the time of the Voyager 2 flyby, has been imaged. The hemispherical extent of the rift system mentioned above and its truncation by the limb led to the inference that the system is global in extent (Greenberg et al., 1991).

The inferred global rift system includes canyons that exhibit asymmetrical, inward-facing normal fault scarps, where in some locations a large single fault scarp defines one side and several small fault scarps define the other side. The canyons are up to 8 km deep. From the 340° Chasma, additional faults that make up the global rift system continue northward, paralleling the eastern edge of Inverness Corona, to Verona Rupes at the limb (Croft and Soderblom, 1991).

As shown in Fig. 1, Arden Corona is located in the equatorial region of Miranda on the leading (western) hemisphere. Elsinore Corona is located on Miranda's equator on the trailing (eastern) hemisphere. Inverness Corona is located near Miranda's south pole, and is the only corona that has been completely imaged. The coronae are surrounded by either the elements of the global rift system, including the 340° Chasma (Croft and Soderblom, 1991; Greenberg et al., 1991), or by cratered terrain. In some locations, scarps within the 340° Chasma are continuous with the scarps bounding Arden Corona, indicating that they may have formed at similar times (Croft and Soderblom, 1991).

Different estimates for the relative ages based on impact crater counts of the coronae exist in the literature due to the differences in techniques of identifying craters (McKinnon et al., 1991). Our consideration of the chronology of events on Miranda relies on the results from Zahnle et al. (2003), which in turn uses crater counts from Plescia (1988). As summarized in Zahnle et al. (2003), Arden and Inverness Coronae are estimated to be 1 Gyr in age with the assumption that the cratering rates in the uranian system are similar to those inferred in the jovian system. In this case, Elsinore Corona and the cratered terrain are estimated to be older than 3.5 Gyr. Alternatively, if the cratering rates are similar to an impactor flux consistent with the large number of small craters on Triton, then Arden and Inverness Coronae may only be

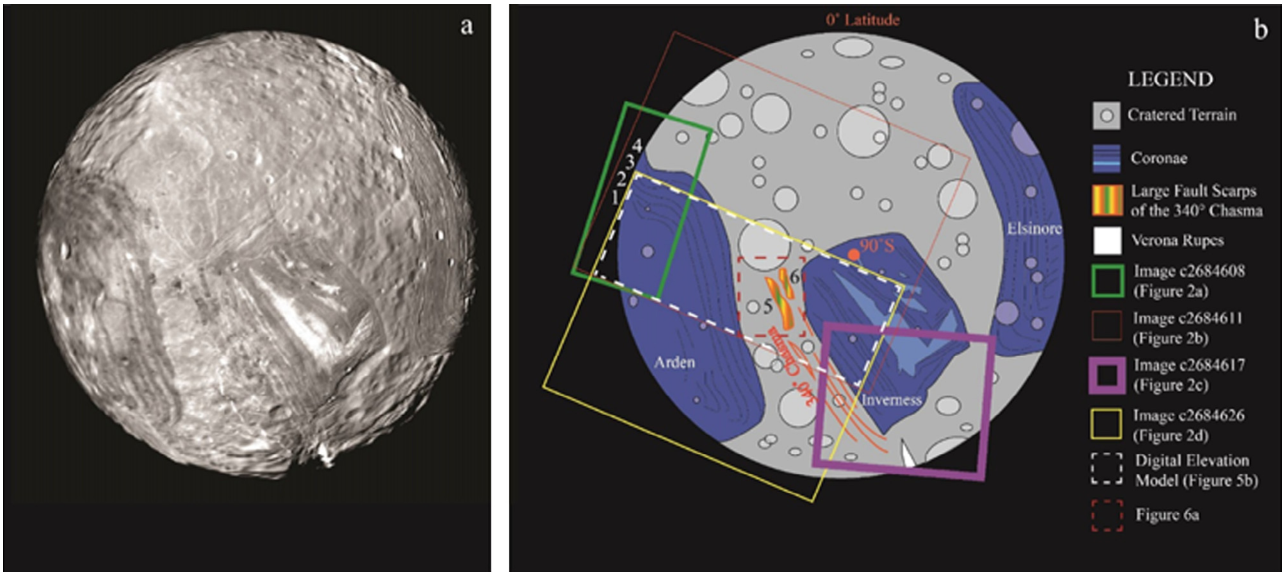

Fig. 1. (a) A global mosaic of Miranda produced by the U.S. geological survey and (b) a map of (a) that shows the coronae, the locations of the ISS images, the DEM used in this study, and the locations of Scarps 1–6.