EXTENSIONAL TECTONICS OF ARDEN CORONA, MIRANDA: EVIDENCE FOR AN UPWELLING ORIGIN OF CORONAE; ***Robert Pappalardo, Ronald Greeley, and Stephen J. Reynolds***, *Department of Geology, Arizona State University, Tempe, Arizona 85287-1404.*

Subparallel ridges and troughs in Arden Corona on Miranda are interpreted as tilt blocks formed by extension and normal faulting of the satellite's lithosphere. Progressive shallowing of some faults to dips of <20° offers the first evidence for low-angle normal faulting on a body other than Earth. Normal faulting in Miranda's coronae was likely induced by diapiric upwelling during partial differentiation and is inconsistent with a competing model, originally proposed by Shoemaker [see *1*], that invokes catastrophic breakup and reaccretion of the satellite.

Miranda exhibits geology that is unique among the Solar System's natural satellites. Voyager 2 images show the satellite to have three large "coronae" within a rolling cratered terrain [*2*]. These ovoidal to trapezoidal regions consist of an outer belt of subparallel ridges and troughs and an inner region of smooth materials and/or ridges and troughs of multiple orientations. Corona origin is controversial, as they might have resulted from induced downwelling or internal upwelling within Miranda [*1,3,4*].

In the downwelling model, Miranda was shattered in its early history by a catastrophic impact and then reaccreted [*1,3*]. Infalling silicate-rich chunks sank through the satellite's ice-rich mantle and stirred downwelling convection currents, forming the coronae at the surface above. If coronae were formed by downwelling currents, the ridges and troughs of their outer belts should be compressional in origin, expressed as folds or reverse faults [*1*]. In the alternative model, upwelling in Miranda's interior involved internally driven diapirism or solid-state convection [*3,4*]. If coronae were formed by upwelling, Miranda's ridge and trough terrain is predicted to be of extensional-tectonic origin, expressed as horst-and-graben structures or tilt blocks [*5,6*]. Thus, the origin of ridges and troughs within coronae is the principal constraint on corona formation.

Global views of Arden Corona show an inner region of bright and dark materials and an outer belt of ridge and trough terrain. Voyager image FDS 26846.26 reveals a cross-sectional view of the southeastern part of the Arden outer belt, seen along the satellite limb. Because the horizon is perpendicular to the local topographic trend, this view can be translated into a cross-section [*7*] which reveals ≈4 km of total vertical relief in a major depression. A topographic rise outboard of the corona shows a broad convex profile, whereas the inboard rise is sharp. The ridges and troughs within the depression are asymmetric, and ridge-to-trough relief is as great as 2 km [*7*]. More subtly, outward-facing slopes shallow progressively toward the corona's outer boundary. The outward-facing ridge walls display 1 km wide bright and dark striations oriented downslope. Commonly, dark material is concentrated near the top of a striated wall. In western Arden Corona, outer belt ridges and troughs are associated with light and dark albedo banding, with bright-and-dark stripes showing paired widths of about 13 km. Ridges show dark, commonly striated walls that face outward from the corona. A few structures visible in bright material are truncated against neighboring dark stripes, and patches of dark and very bright materials are present.

After considering the detailed morphological expressions of the processes that can create subparallel ridges and troughs on icy satellites [*6*], we interpret the features of the Arden outer belt as due to tilt block style normal faulting in response to extension, the striated walls within Arden Corona being normal fault scarps that dip consistently outward. Subsurface dark material is commonly exposed near the tops of fault scarps and moves downslope. Tilt blocks observed in profile along the limb in southeastern Arden Corona are defined by low angle normal faults. Progressive shallowing of faults toward the outer boundary of the corona requires a listric fault geometry [*8*]. Fault dips at the surface are probably ≈50° before significant fault-block rotation, shallowing to ≈10°. Fault reconstruction shows that the extension across the southeastern Arden rift zone is about 90%. Although not unusual on Earth, this extension is extreme compared to previous estimates of strain on Miranda and other icy satellites, which are typically a few percent [*3,9*].

The convex outer boundary of Arden Corona likely resulted from rollover of the outboard hanging wall, as expected above a listric normal fault [*10*]. The uplifts flanking the depression are probably explained by flexural warping of the lithosphere in response to isostatic buoyancy forces. Following the method of Vening Meinesz [*11*], the ~2 km uplift of the inward rift shoulder can be non-uniquely modeled by a cold elastic ice lithosphere (density = 9200 $kg \cdot m^3$, Young's modulus = 10^4 MPa, Poisson's ratio = 0.33) of effective thickness 50 km resting on a fluid substrate of density ≈1050 $kg \cdot m^3$. The outboard uplift might result from similar flexural processes [*12*] or thinning of a "lithospheric mantle" which uplifts isostatically as it thins along a zone of pure or simple shear [*13*].

Ridges and albedo striping in western Arden Corona are likewise interpreted as shaped by normal faults that dip outward from the corona. Bright ridge faces represent original cratered terrain surfaces back-tilted by rotational normal faulting, and dark, commonly striated walls are fault scarps exposing dark subsurface material. This accounts for the pairing of bright and dark albedo stripes, the truncation of structures (craters) in bright material by dark scarps, and the termination style of Arden ridges. This is also consistent with an increase in the ratio of outward-facing (fault scarp)

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slopes to flatter (tilt block) faces visible in western Arden as the Voyager viewing geometry changes from down-looking to highly oblique. Photometric studies show that bright material within the Arden outer belt has an albedo indistinguishable from cratered terrain, suggesting it is the same material [*14*]. This is consistent with tectonic disruption of cratered terrain to form the outer belt, as in the tilt-block model. In eastern Arden Corona, bright outward-facing scarps appear to cut a region of dark material. These scarps appear brighter than their surroundings because of oblique solar illumination or because they reveal bright material that underlies the dark material.

This evidence presents a unified picture of extensional tectonics affecting Arden Corona, in which outward-facing fault scarps shaped its entire outer belt. A tilt-block interpretation of the ridges and troughs in southeastern Arden Corona has been considered by others [*3*,*7*,*15*], and it has been suggested that outward-facing normal faults have shaped or modified at least part of Arden Corona's outer belt and that this belt may be extensional [*3*]. However, no one has recognized the low-angle attitude of the normal faulting in southeastern Arden or the general relationship of this region to Arden Corona tectonics; furthermore, we provide specific evidence to conclude that tilt-block style normal faulting accounts for the ridge and trough topography and the albedo striping throughout the corona's outer belt.

Extension in the Arden outer belt indicates an upwelling origin for Arden Corona and is inconsistent with the sinker model of corona evolution. The outward-facing direction of faults suggests doming of the corona interior and sloughing of the outer ridge and trough belt. Support for an upwelling origin for Miranda's coronae also follows from the morphology of ridges and troughs in Inverness Corona and Elsinore Corona, likely shaped by similar volcano-tectonic processes in response to extensional stress [*16*]. Major corona-bounding depressions, analogous to that of southeastern Arden, are likewise observed in limb profiles crossing the western boundary of Arden Corona and the boundaries of Elsinore Corona [*7*]; these depressions and their flanking topographic highs were probably created around each corona by rifting and flexural processes analogous to those described above in response to internal upwelling. A tilt block origin for ridges and troughs in Arden Corona follows a general model in which normal faulting and fissure volcanism can combine to produce a spectrum of possible morphologies that accounts for most ridge and trough terrain on icy satellites [*17*].

Either solid-state convection or large-scale diapirism during partial differentiation might have induced corona formation. Models of convection in a sphere predict that a pattern of four or six symmetrically distributed regions of concentrated upwelling can form at low Rayleigh number and persist as Rayleigh number increases, but only when a significant fraction of heat is supplied from a core below [*18*]. This is marginally possible for a differentiated Miranda that gets the bulk of the ~100 K temperature rise necessary to induce solid state convection from tidal heating which deposits heat within the mantle instead.

Although the riser model predicts a zone of concentric extensional structures surrounding an inner region of disorganized extensional structures, the actual squared shape of Miranda's coronae might be explained by superposition of a concentric upwelling-induced stress field onto a pre-existing structural grid [*19*]. Alternatively, modeling shows that downwelling material confined to a sphere has a slab-like geometry [*18*], and interaction between contemporaneously formed coronae might induce "flattening" of their adjacent sides in response to inter-corona downwelling [cf. *20*].

In summary, the outer belt of Arden Corona on Miranda was shaped by tilt-block style normal faulting, in which outward-facing scarps generally expose dark material. This explains both the topography and albedo patterns in Arden Corona. In a rift that bounds the corona, we recognize the first evidence for low-angle normal faulting on a body other than Earth, and we estimate a local extension of ≈90%. Arden Corona observations contradict the compressional-tectonic predictions of the "sinker" model of corona evolution. Instead, an extensional-tectonic origin supports formation of Arden Corona in response to internal upwelling. Thus, Miranda likely had an endogenic, rather than a catastrophic, geological history.

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