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Supporting Information for

[Tectonism and Enhanced Cryovolcanic Potential Around a Loaded Sputnik Planitia Basin, Pluto]

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Contents of this file

Additional Supporting Information (Files uploaded separately)

Introduction

The Supporting Information includes Text S1, S2, and S3, which respectively describe the concept behind the FEM Model Grids used in our simulations (accompanied by Figures S1 and S2 that show the entirety and a detail of the model domain), the definition of the coordinate system used in our analysis, and a justification for using the "crustal collar" loads in our analysis. We also include Figures S3 through S11 depicting model stress and topography results spanning the range of our parameter space, and Dataset 1, which is a zipped folder containing the ArcGIS shape files and auxiliary files for the mapping of Pluto's tectonism and the boundaries of Sputnik Planitia and the Sputnik basin that are presented in Figs. 1 and 2 of the main text. Finally, we issue a statement on an upcoming change to the Pluto-Charon coordinate system and how it affects interpretation and future use of the products provided here.

Text S1: FEM Model Grids

The Finite Element Method (FEM) discretizes the modeled domain into numerous contiguous "elements" that facilitate the solution of partial differential equations via matrix techniques. Figure S1 shows the extent of the model domain, anchored on the symmetry axis at radial coordinate value r = 0 (using the first definition of "radius" defined in the *Coordinate Systems* sub-section above). Individual elements (of order a km or so in width) are too small to be resolved at the scale of this figure. Figure S2 shows a close up of the model domain near the location of the modeled basin. Individual elements can be distinguished in this figure, giving an impression of the resolution of the model and the scale of the overall calculation.

Text S2: Coordinate System

We use the planar axisymmetry mode of COMSOL, with distances reckoned by radius r from the symmetry axis and vertical coordinate z. However, in the study of planets there are two other useful definitions of the term "radius", requiring clarification of such terminology here. The second such definition, given above, is the radial distance from the center of the planet, defined here as the origin, also corresponding to the COMSOL origin at (r, z) = (0, 0). The third is the distance from a central point to another point(s) measured along the (curved) planetary surface in map view. We plot model quantities (Figures 5-12, 14, S3-S11) using this third definition, termed the "projected radial distance" r_{proj} at the model surface, itself defined by the mean radius (second definition) of Pluto at 1188 km. When we use the terms "radius" or "radial" in this paper, we are generally referring to this third definition, and we use r_{proj} in this sense. For points at the surface (e.g., the "A" components of each of Figures 5-6, 8, S3-S11), this definition is straightforward. For points beneath the surface, either within the lithosphere or on the depressed central surfaces of the model impact basins, we assign r_{proj} (first definition) based on the value of r_{proj} of the point at the planetary surface that lies along the same radius line (second definition) drawn from the center of the planet. This projection from a curved to a rectilinear display (elevation vs. r_{proj}) allows for an economical display of the model results. We will define the variable z as vertical coordinate of the models, in the sense of the second definition given above; the depth below the radius of Pluto R_p measured along a line radiating from the planet's center.

Text S3: Justification for Crustal Collar Loads

Crustal collar loads are suggested by impact hydrocode models, are detected by gravity at lunar basins, and are implicated in the origin of mascon gravity signals. This load appears necessary to explain rim topography, since the low amount of flexure for this load configuration will not produce much of the observed rim topography, although some of that topography is likely due to ejecta (McKinnon et al., 2017). But the timescale of response to crustal collar loads for basaltic planets is determined by the relaxation time of the underlying mantle. Under our lithospheric modeling scheme, an icy planet's ocean (as the fluid substrate to the shell) is the equivalent of the mantles of silicate planets. However, the difference between silicate mantles and Pluto's ocean "mantle" is that the latter has a very low viscosity, such that the response would be more or less instantaneous, versus the drawn-out response times of the former (typically 10^3-10^6 years for Earth's mantle). Thus, the time scale of the impact response becomes relevant. In hydrocode models, the largest deformation occurs plastically, whereas the models in this paper consider elastic response to loading. If for some reason the surface material reaches its final post-impact configuration before the subsurface crustal collar does, then the response we are modeling here is relevant. If the surface material reaches this configuration after the collar does, then this loading would not have the same effect as modeled (although some topographic effect might be seen). If the timescales are the same, it is plausible that the crustal collar models presented here are relevant.

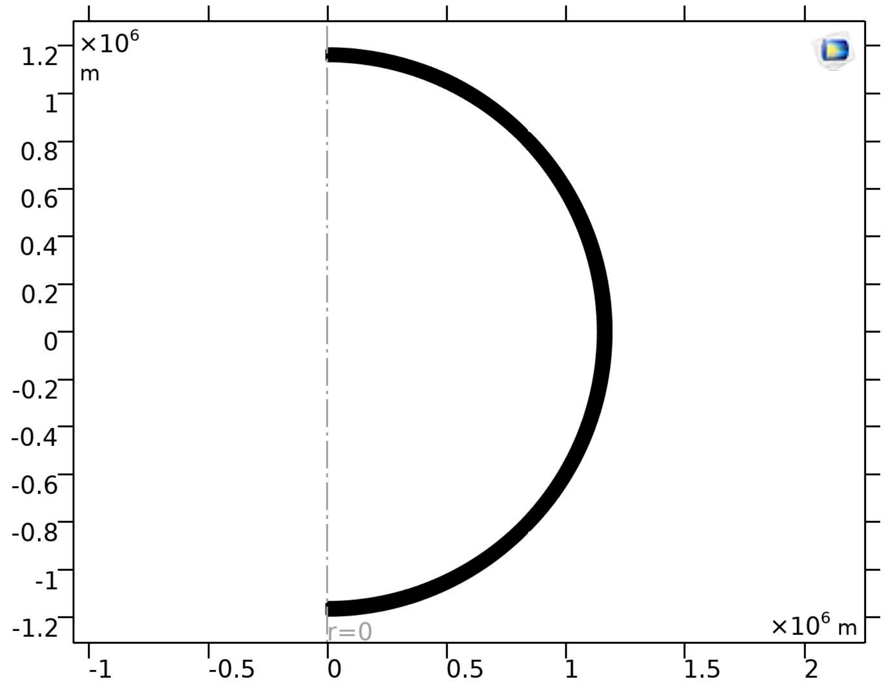

Figure S1. Entire geometry of the spherical shell finite element grid for the nominal model (T_e = 50 km) of Pluto's ice elastic lithosphere around SP. Individual elements are not visible at this resolution.

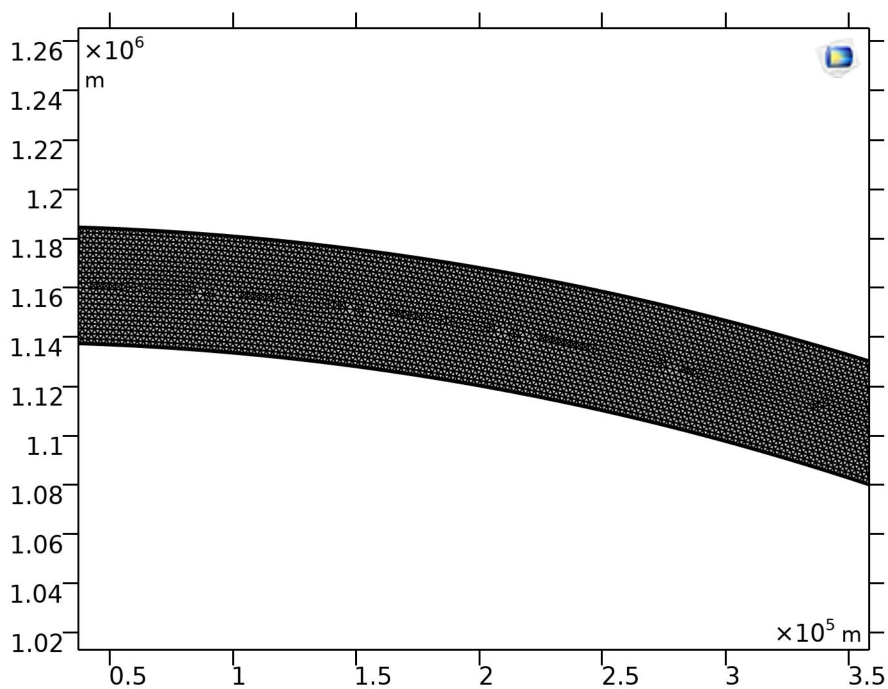

Figure S2. Close up of the model of Figure S1 near the symmetry axis at the location of the model basin.

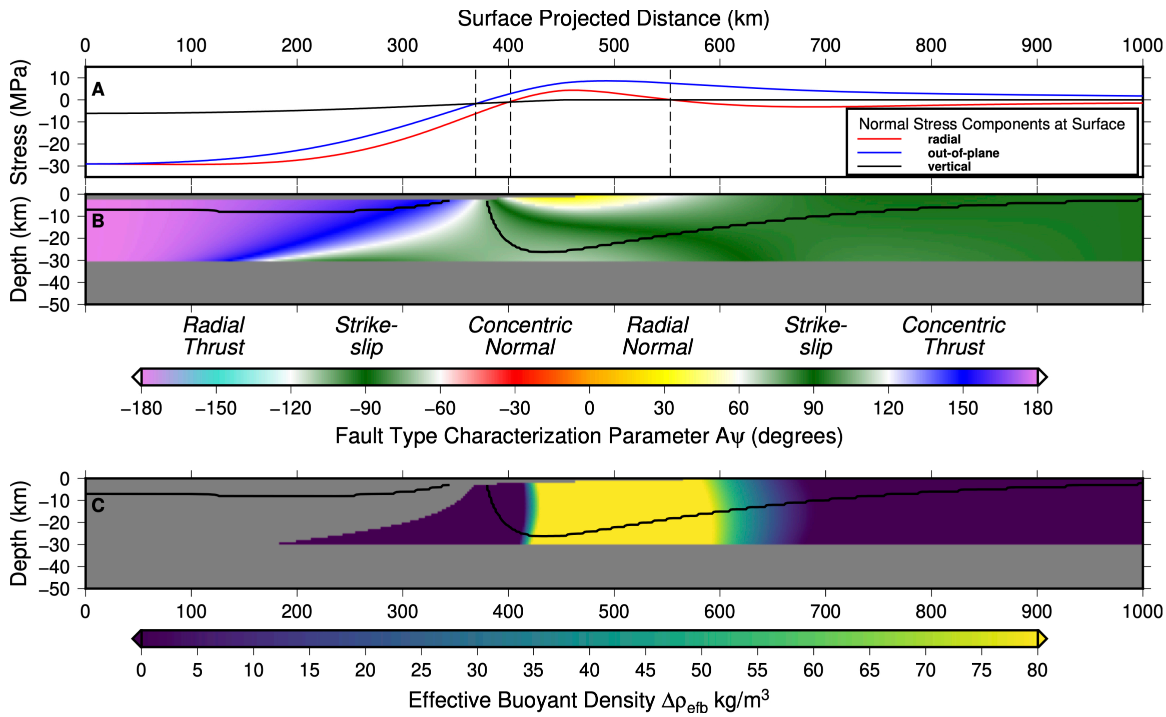

Figure S3. As in Figure 5, for model U30N, T_e = 30 km. Note greater range on stress scale relative to previous Figures.

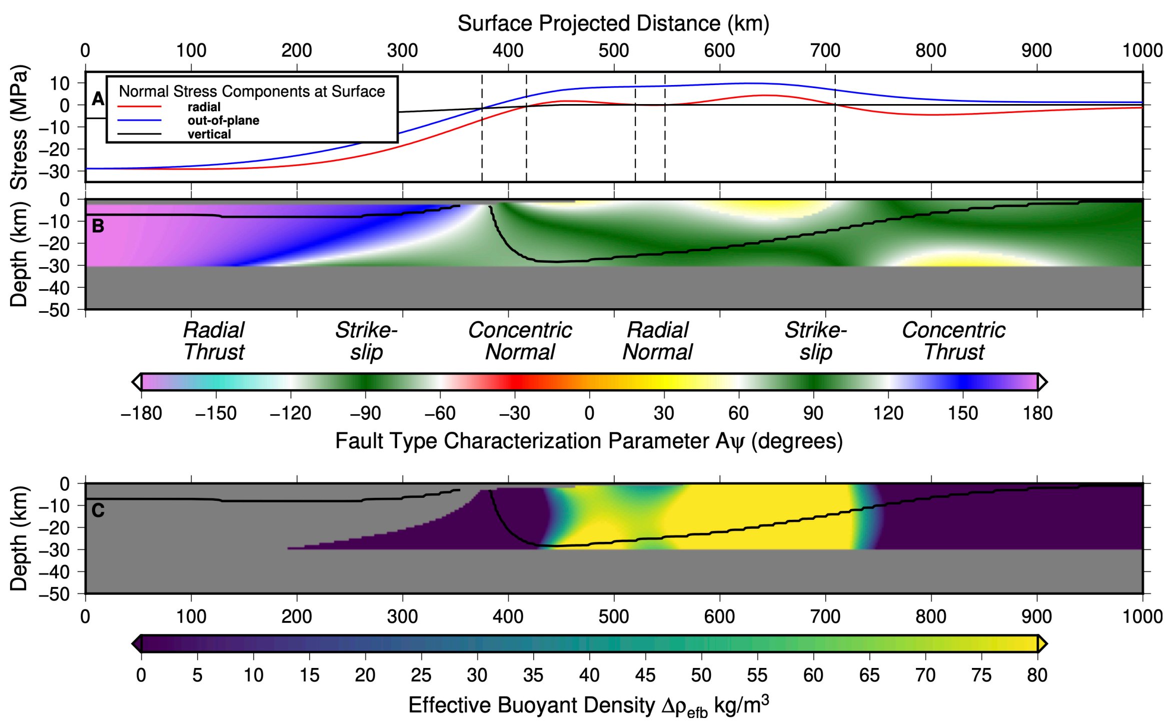

Figure S4. As in Figure S3, for model U30CO, featuring a crustal collar buoyant load.

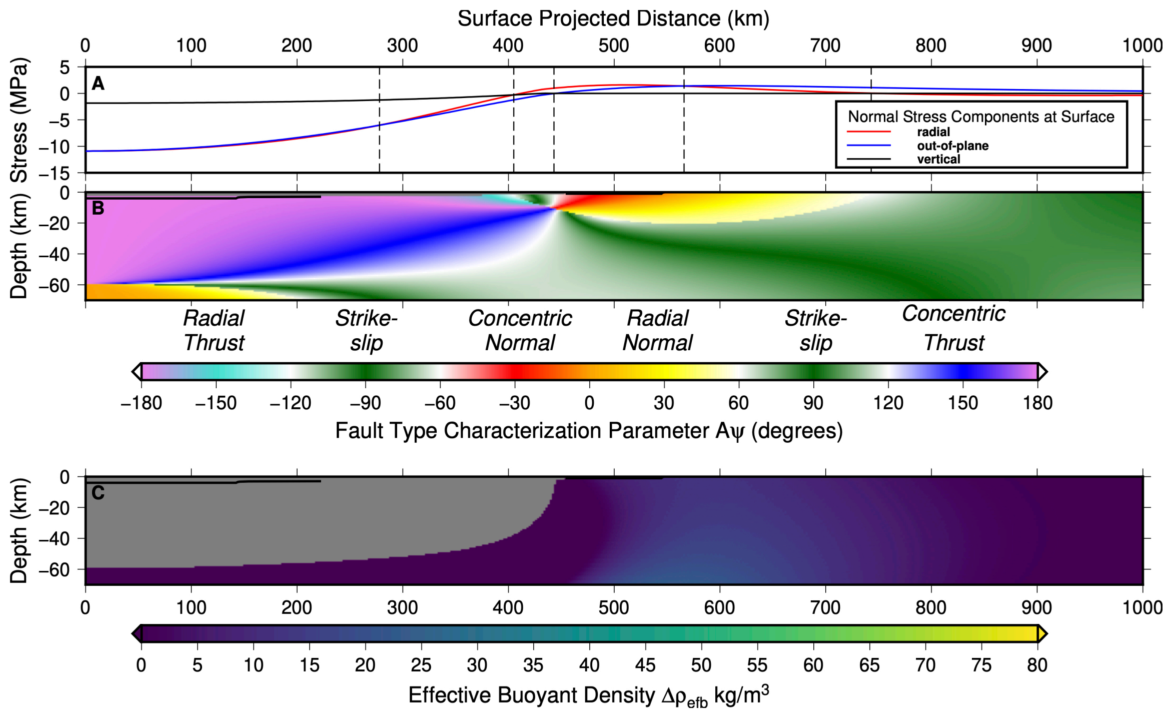

Figure S5. As in Figure 5, for model U70N, T_e = 70 km . Note that the stress and depth vertical axes have lesser and greater ranges, respectively, than for previous figures.

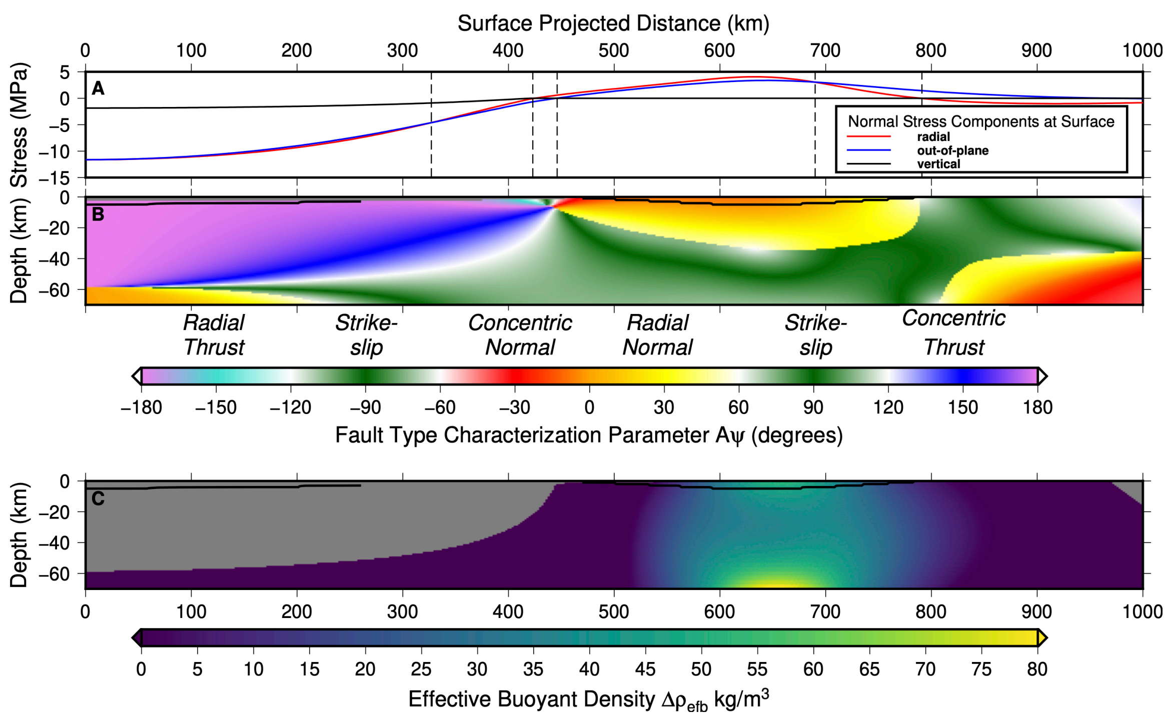

Figure S6. As in Figure S5, for model U70C0, featuring a crustal collar buoyant load.

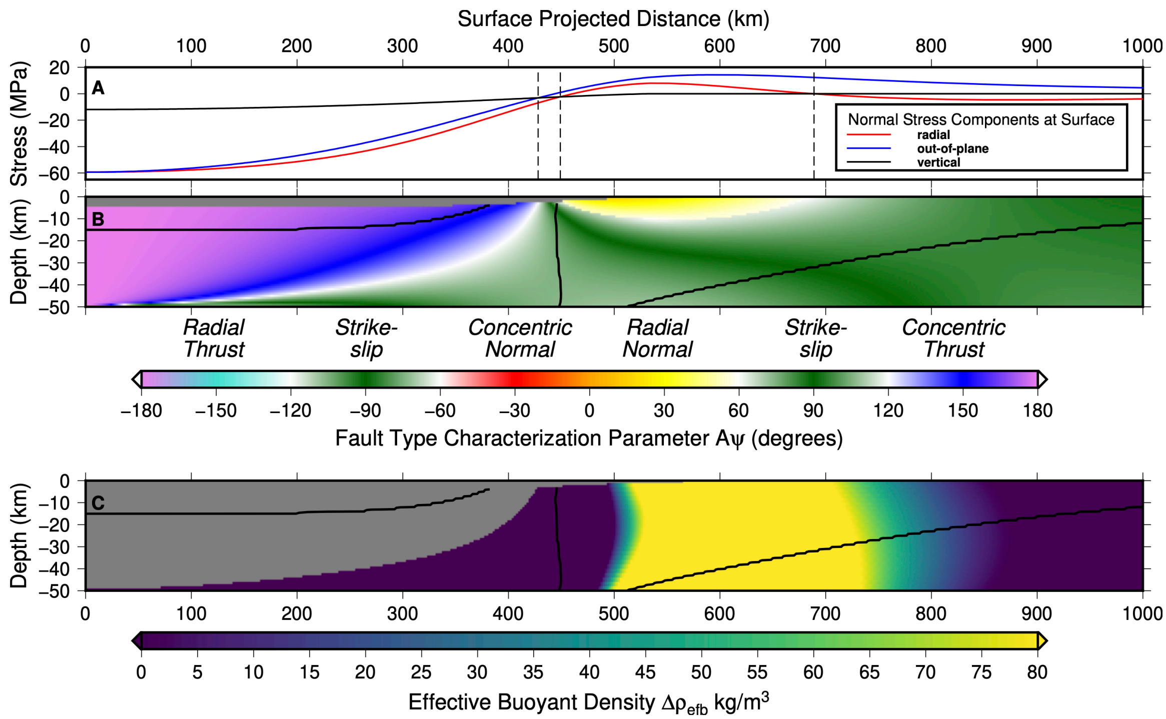

Figure S7. As in Figure 5, for model U50D5, featuring initial basin center depth d_{bc} = 5 km. Note greater range on stress axis than previous figures.

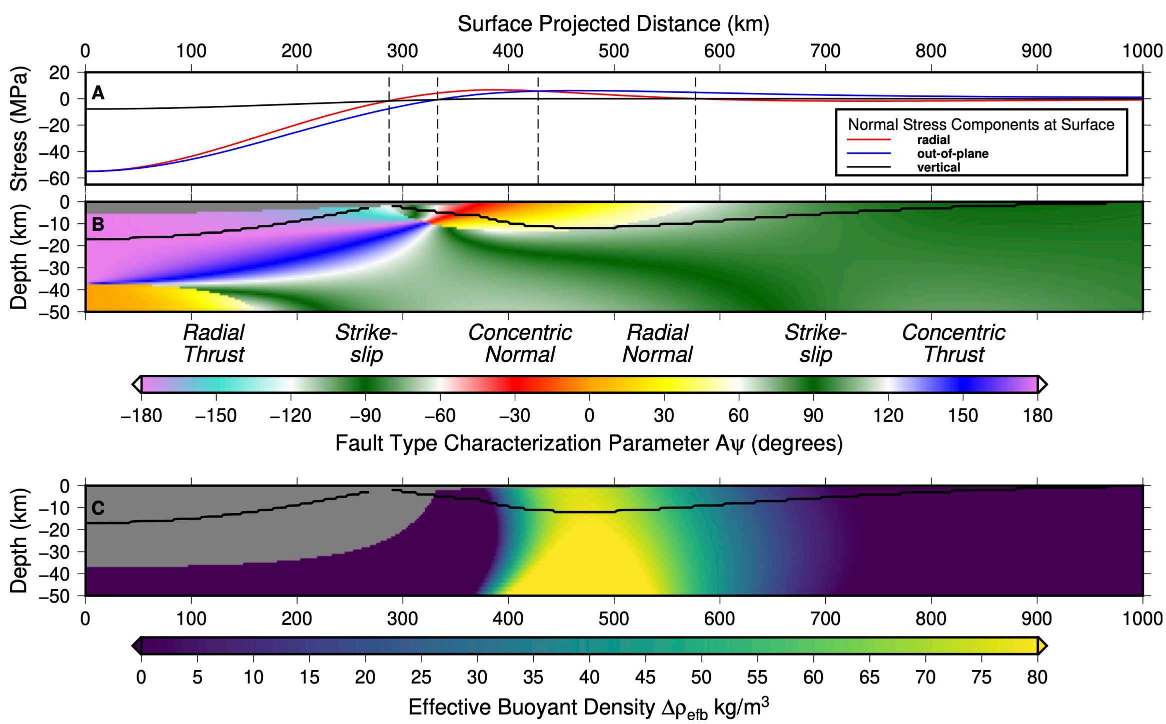

Figure S8. As in Figure 5, for model U50B6, featuring a "bowl-shaped" load and d_{bc} = 6 km. Note greater range on stress axis than previous figures.

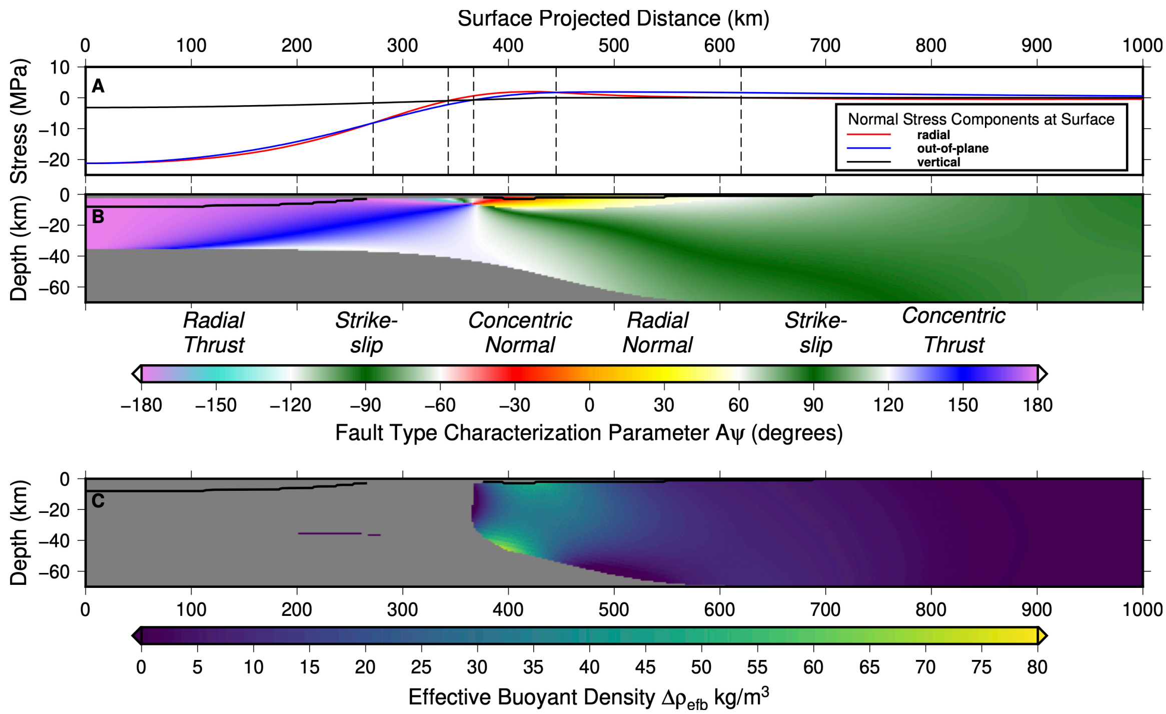

Figure S9. As in Figure S5, for model C70N, featuring compensated initial basin topography.

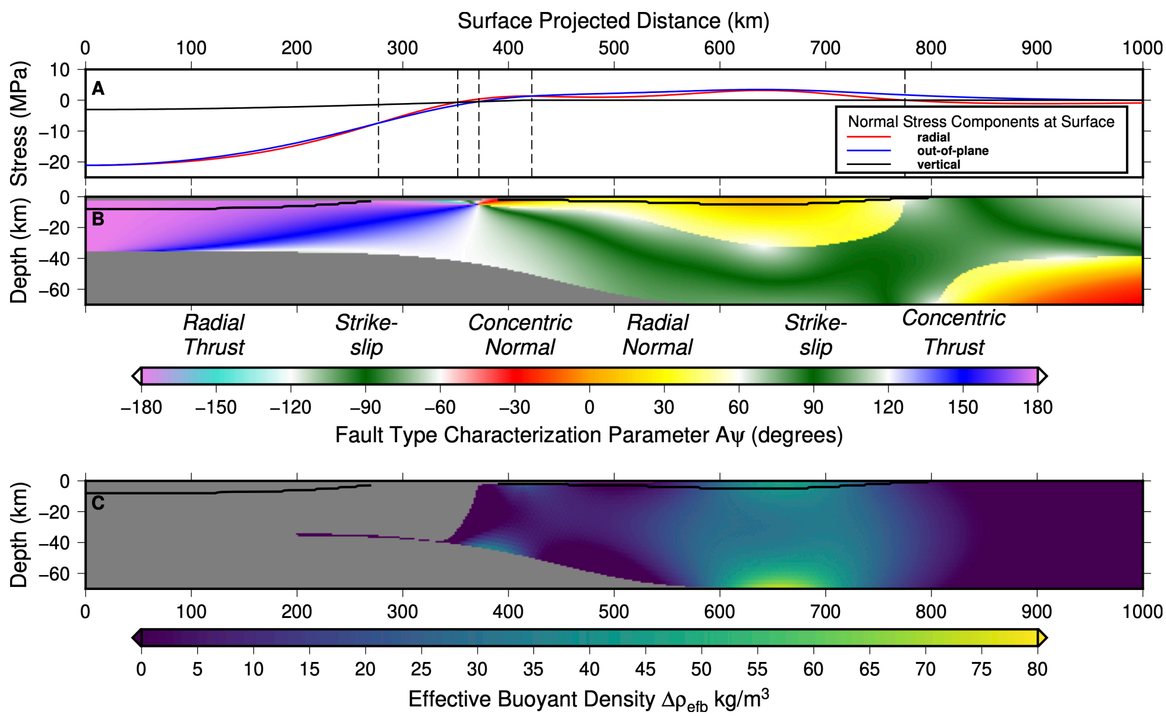

Figure S10. As in Figure S9, for model C70CO, featuring compensated initial basin topography and crustal collar load.

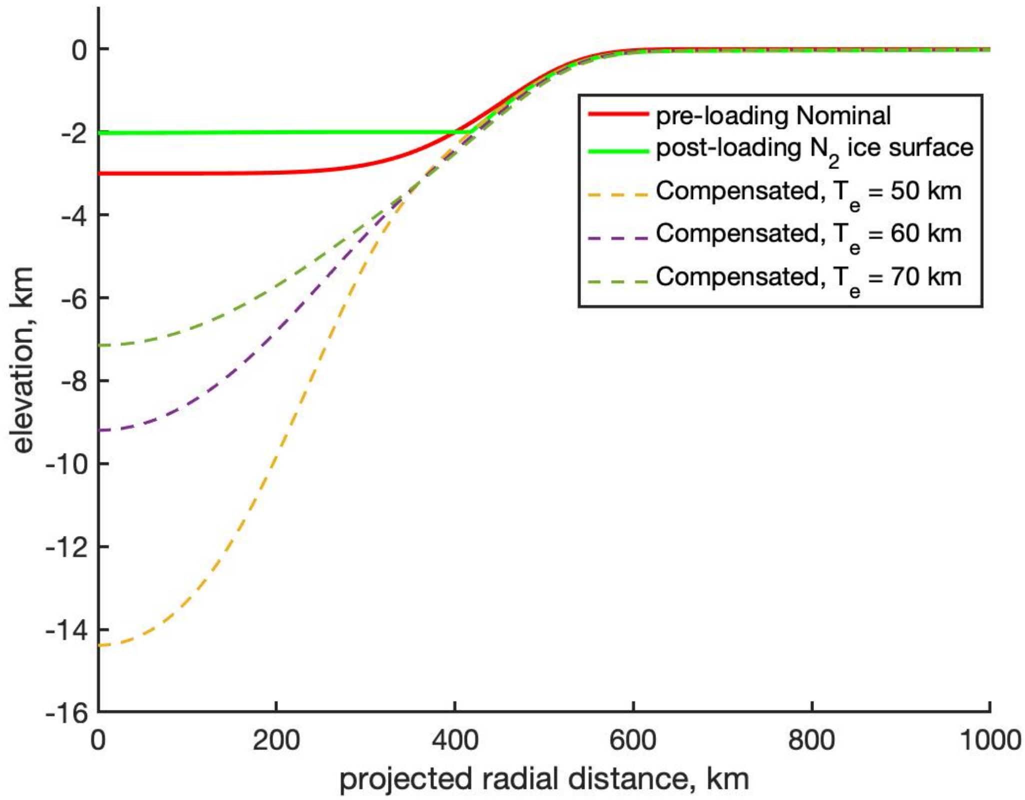

Figure S11. Topography, as in Figure 7, for models with compensated initial basin topography.

Data Set S1: Mapping Files

The tectonics mapping presented in Fig. 2 was performed in ArcMap 10.3.1, and we include the ArcGIS shape files and auxiliary files for the eight mapped tectonic systems, the depressions of the ridge-trough system, the boundary of Sputnik Planitia, and the approximate topographic rim of the Sputnik basin,in a zipped folder included with the Supplementary Material entitled “ds01.zip”. The files are named according to each system and feature as shown in Figs. 1 and 2, and the shape files (.shp extension) can be read into ArcGIS or the free-to-download QGIS software. The base maps we used for mapping include the LORRI-MVIC global mosaic and the global stereo digital elevation model of Pluto, both projected at 300 m/pixel. These are archived in the PDS Imaging and Cartography Node, and can be downloaded at the following links:

Global mosaic:
https://astrogeology.usgs.gov/search/map/Pluto/NewHorizons/Pluto_NewHorizons_Global_Mosaic_300m_Jul2017

Global DEM:
https://astrogeology.usgs.gov/search/map/Pluto/NewHorizons/Pluto_NewHorizons_Global_DEM_300m_Jul2017

Readers should note that in early 2021 the New Horizons team discovered that there was an issue with the coordinate system being used for Pluto and Charon, whereby Pluto had a Charoncentric longitude of 1.45°E during the flyby (and Charon a Plutocentric longitude of 1.45°E), not 0° as expected by definition. It was found that the planetary constants file pck00010.tpc appeared to be inconsistent with the Charon orbit, both in zero point and rate, and assuming that the orbit is better determined than the rotation, the PCK has been adjusted in order to match the orbit. At the time of publication, however, the mosaic and DEM archived in the links shown above have not been corrected for this issue, but will be in the near future, upon which our tectonics mapping will be slightly shifted relative to the mosaic and DEM. As such, readers who download the ArcGIS shape files should make sure to examine these links for versions of these maps that were uploaded prior to August 2021 (if an updated version of a data product emerges, the USGS flags the web page to highlight that the product has been superseded), as the coordinate systems of these earlier maps will match that of our tectonics mapping, and so can be used as base maps.