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Could Pantheon Fossae be the result of the Apollodorus crater-forming impact within the Caloris basin, Mercury?

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ABSTRACT

The ~40-km-diameter Apollodorus impact crater lies near the center of Pantheon Fossae, a complex of radiating linear troughs itself at the approximate center of the 1500-km-diameter Caloris basin on Mercury. Here we use a series of finite element models to explore the idea that the Apollodorus crater-forming impact induced the formation of radially oriented graben by altering a pre-existing extensional stress state. Graben in the outer portions of the Caloris basin, which display predominantly circumferential orientations, have been taken as evidence that the basin interior was in a state of horizontal extensional stress as a result of uplift. If the Apollodorus crater formed at the time of such a stress state, impact-induced damage to basin fill material would have caused basin material to move radially outward, leading to a decrease in the radial extensional stress and an increase in the circumferential stress. If this change in differential stress was sufficient to induce failure, the predicted style of faulting would be radial graben extending outward from the exterior crater rim. The ~230-km radial extent of Pantheon Fossae implies, by this scenario, that the Apollodorus impact generated a large damage zone, extending to perhaps three crater radii (~60 km) or more. The calculations also suggest, under this scenario, that the Caloris basin fill had greater strength than the surrounding crust and that the basin uplift and extensional stress field prior to the Apollodorus impact were close to azimuthally symmetric. The location of Pantheon Fossae very near the center of the Caloris basin appears to be coincidental; any crater similar in size to Apollodorus and located within ~300 km of the basin center could have produced a radiating set of graben by the mechanism explored here.

1. Introduction

One of the most remarkable surface features imaged by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft during its first Mercury flyby (Solomon et al., 2008) was Pantheon Fossae (Fig. 1), a complex of troughs radiating from a location near the center of the Caloris impact basin (Murchie et al., 2008; Watters et al., 2009-this issue). The troughs are interpreted as simple graben formed in response to near-surface extensional stresses in the basin interior. The radially oriented graben appear to be part of a larger pattern of extensional features within the basin floor; beyond about 300 km radial distance from the basin center the graben are more typically circumferential to the basin rather than radial, although radial trends are also seen and the distal graben in places form a polygonal pattern (Watters et al., 2005). Pantheon Fossae is noteworthy as well because within a few kilometers of the projected center of the radiating pattern of troughs is the ~40-km-diameter Apollodorus crater. The near-coincidence of the center of symmetry for Pantheon Fossae and Apollodorus crater raises the question as to whether the two features are causally related. Although explanations for Pantheon Fossae unrelated to Apollodorus crater have been suggested (Head et al., 2008; Murchie et al., 2008; Watters et al., 2009-this issue), in this paper we examine the hypothesis that the two features are physically linked. Specifically, we explore whether the Apollodorus crater-forming impact modified the state of stress within the central Caloris basin floor in a manner that led to the formation of many, if not all, of the graben of Pantheon Fossae.

We begin with a brief overview of the imaging observations of Pantheon Fossae, Apollodorus crater, and their geological relations to other features within the floor of the Caloris basin. We then explore constraints on and models for the state of near-surface stress within the Caloris basin at or near the time of the Apollodorus crater-forming impact. We apply the concept of impact-induced damage to estimate, by means of finite element models, the change in lithospheric stress and strain that would accompany such an impact. We investigate the affect on those solutions of different assumptions regarding the

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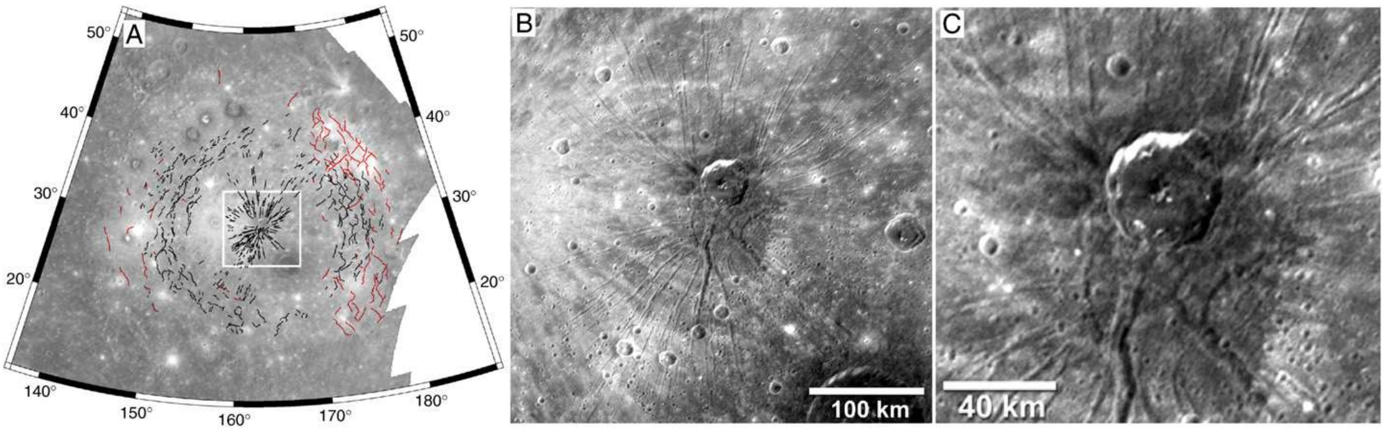

Fig. 1. (A) Tectonic map of the Caloris basin showing graben (black) and wrinkle ridges (red), overlaid on a high-resolution narrow-angle camera mosaic constructed from MESSENGER and Mariner 10 images. (B) MESSENGER image of Pantheon Fossae; the area of the image is indicated by the white box in (A). (C) Close-up of Apollodorus crater and its relation to the proximal graben of Pantheon Fossae. Adapted from Murchie et al. (2008).

detailed state of stress at the time of impact, the radial extent of damage, the thickness of the mechanical lithosphere at the time of impact, and any contrast in strength between different rock types within the Caloris basin floor. We also explore the sensitivity of the models for stress state change to the particular location of the Apollodorus impact relative to the center of the basin. We conclude with an assessment of the likelihood that the formation of the Apollodorus crater led to the formation of the graben of Pantheon Fossae, as well as the future observations that would permit the idea to be tested further.

2. Observations of faulting within Caloris basin

Pantheon Fossae consists of more than 200 linear troughs that radiate out from a locus near the center of the Caloris basin (Fig. 1, Murchie et al., 2008; Watters et al., 2009-this issue). The graben range in length from about 5 to 110 km and in width from less than 1 km to as much as 8 km (Murchie et al., 2008). A large number of graben extend outward from the center of the Caloris basin in virtually all directions to radial distances as great at 230 km. Some graben continue outward to greater distances within limited azimuthal bands (Murchie et al., 2008; Watters et al., 2009-this issue), and the distal portions of some of the radiating graben were seen in Mariner 10 images and mapped as part of the polygonal pattern of basin-concentric and basin-radial troughs in the eastern portion of the outer Caloris basin floor (Strom et al., 1975; Watters et al., 2005). Nowhere are the graben embayed by interior smooth plains deposits, implying that the faulting postdates the partial volcanic infilling of the basin (Murchie et al., 2008).

The Apollodorus crater, 41 km in diameter, is located near the center of the Pantheon Fossae complex. Like several other large craters in the floor of Caloris, Apollodorus exposed low-reflectance material, distinct in spectral properties from the Caloris interior plains (Robinson et al., 2008), on its rim, wall, and floor at the time of impact (Murchie et al., 2008; Watters et al., 2009-this issue). The graben of Pantheon Fossae do not disrupt the Apollodorus crater rim and do not extend inward to the crater walls or floor. Low-reflectance material ejected by the Apollodorus crater-forming impact overlies and obscures the inner portions of Pantheon Fossae graben complex. This relationship implies that the deposition of ejecta from Apollodorus postdated the formation of those graben (Murchie et al., 2008; Watters et al., 2009-this issue). In the context of the scenario explored in this paper, this last observation limits the timing to situations in which at least the innermost graben formed at the approximate time of formation of the Apollodorus transient cavity.

3. Pre-Apollodorus stress state

If the Apollodorus crater is related to the formation of Pantheon Fossae, a likely explanation is that the Apollodorus impact modified a pre-existing state of stress. We presume that the stress state immediately prior to the formation of the Apollodorus crater may be specified by one of the recent models of Kennedy et al. (2008) for stress and deformation in and around the Caloris basin. In that study a series of axisymmetric finite element models were used to test a range of lithospheric loading scenarios to account for the observation from Mariner 10 images that predominantly basin-concentric contractional features predate dominantly basin-concentric extensional features on the outer floor of the basin (neither the innermost portions of the floor nor the entire western half of the basin were imaged during the Mariner 10 flybys). From these axisymmetric models, it was shown that the earlier contractional features on the basin floor are consistent with subsidence accompanying a flexural response to partial basin infilling by smooth plains deposits, presumed to be volcanic in origin. A variety of fill thicknesses, emplacement scenarios, and lithospheric thicknesses are consistent with the observed pattern of interior contractional faulting associated with subsidence.

Models that accounted for the locations of contractional features to 500-km radial distance from the basin center required surface loading of nearly uniform thickness over most of the basin. This result suggested that the pre-fill Caloris basin floor was flatter than the geometry inferred for similar-sized basins on the Moon (Watters et al., 2005; Fig. 2 of Kennedy et al., 2008). This inference of a flat basin floor was in part based on an assumed basin diameter of 1300 km as indicated by Mariner 10 observations. MESSENGER observations, in contrast, suggest a basin diameter of about 1500 km (Murchie et al., 2008), which enables basin fill to extend farther from the basin center. A larger basin allows for a partial relaxation of this implied flat-floor geometry, as it becomes easier to explain contractional features to 500 km if the fill extends to 750 km. The basin floor geometry factored greatly in the prediction of where contractional features should be found, but not significantly in the analysis of later extensional features. As the latter are the focus of the present study, the same flat floor geometry as used previously is assumed here, though it is extended to a radius of 750 km.

Following an earlier proposal by Melosh and McKinnon (1988), Kennedy et al. (2008) showed that a later stage of normal faulting within the basin interior could be explained by the emplacement of exterior smooth plains within an annular zone that extends from 1 to 3 basin radii from the basin center. Though inducing subsidence of the external plains, this load also leads to uplift of the basin. In order for this uplift to yield extensional stresses sufficient to overcome residual

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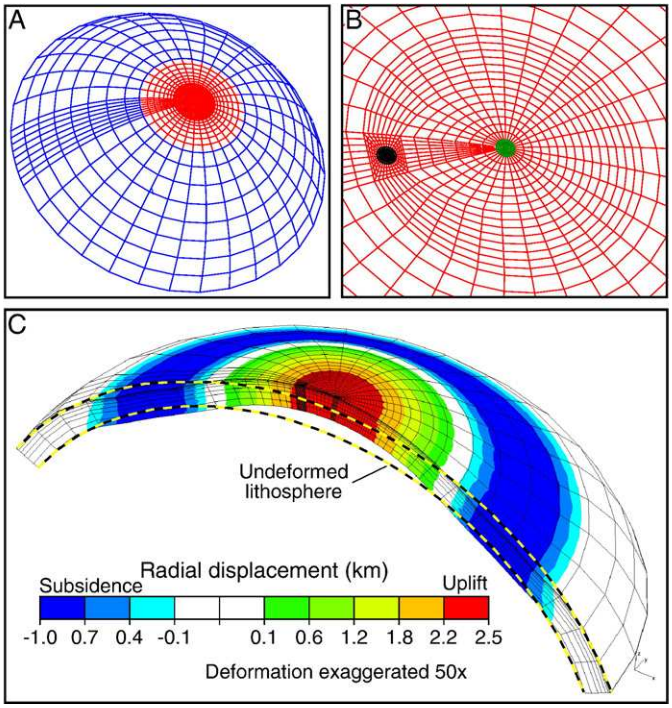

Fig. 2. (A) 3-D spherical finite element model covering a cap extending radially to 80° of arc and to a depth of 400 km; the 1500-km-diameter Caloris basin is shown in red. Element size decreases toward the basin center to provide greater resolution in this region. (B) Close-up of basin center showing the ~40-km-diameter Apollodorus crater (green) at the center of Caloris basin and a similar-sized crater (black) offset 200 km from the basin center. (C) Calculated deformation of Mercury's lithosphere due to loading associated with the external smooth plains assumed to completely surround the Caloris basin between radial distances of 850 and 1850 km from the basin center. Subsidence of the smooth plains is shown in cool colors, while the resulting uplift of Caloris basin is shown with warm colors.

compressive stresses in the basin, either the external load must be fairly thick (>5 km) or the residual compressive stresses after interior loading and deformation must have been relatively small. Residual compressional stresses in the basin could have been small if the infilling of the basin floor occurred in stages spaced over a time frame longer than the timescale for basin subsidence in response to a single interior load. In such a case, the uppermost layer of basin fill would experience only those compressional stresses associated with subsidence of this layer.

Whereas our previous study considered a spherical axisymmetric finite element model to explore the pre-Apollodorus stress state, we here utilize a spherical three-dimensional (3-D) model (Fig. 2) to calculate the change in stress induced by the impact. Although most of the geometries and loading configurations considered here are axisymmetric, the 3-D model enables us to examine non-symmetric scenarios such as those in which Apollodorus is offset from the basin center (Fig. 2B), as well as those with non-symmetric exterior smooth plains loading. Kennedy et al. (2008) used Tecton (Melosh and Raefsky, 1980) as a solver. Here we use the viscoelastic finite element program I-deas, which provides an ability to develop and solve spherical 3-D models and was applied in several previous tectonic studies (e.g., Freed et al., 2006, 2007). Parameters describing the elastic constants and flow laws used in the models follow those of Kennedy et al. (2008) unless otherwise mentioned below.

For the present study we initially reproduce a pre-Apollodorus stress state similar to that of Kennedy et al. (2008). As in that analysis, applied surface loads induce a gravity-driven steady-state flexure of the lithosphere, as determined by allowing the asthenosphere to relax fully (to a point of minimal differential stress). In this type of calculation, the magnitude of the viscosity of the asthenosphere does not influence the results. The side edge and 400-km-deep bottom edge of the model are fixed in all directions. Testing of these conditions confirmed that the boundaries are at sufficient distance from the region of flexure so as not to influence the stress state within the modeled basin. In particular, the fixed bottom boundary is isolated from influencing stresses in the lithosphere by the intervening weak asthenosphere. As in the previous study, a 50-km-thick crust is assumed along with a lithosphere that varies in thickness between 60 and 200 km; all layers are assigned an elastic modulus of 10^{11} Pa (except where reduced crustal strength is invoked to investigate the influence of an impact-damaged crust on stress states within the basin fill). We initially apply a basin fill load (out to 750 km from the basin center), which induces subsidence and horizontal compression of the basin interior. After completion of interior subsidence, an external annular load (850 to 1900 km from the basin center) induces subsidence of these external plains and uplift and horizontal extension of the Caloris basin interior (Fig. 2C).

The stress state in the upper portion of fill (1 km thick) within the Caloris basin after an initial stage of loading-induced subsidence (0.5 km) and a later stage of uplift (2 km) produced by the emplacement of exterior smooth plains is shown in Fig. 3. Prediction of the orientation of extensional features produced in response to this extensional stress state depends on the relative magnitude of the horizontal radial and circumferential stresses. As shown in Fig. 3, where radial stresses are more extensional than circumferential stresses, circumferential graben are predicted (between about 250 and 700 km from the basin center). Where radial and circumferential stresses are of similar magnitude (between the basin center and ~250 km radial distance), graben have no preferred orientation. Though this model yields reasonable correspondence with the location of observed circumferential graben within the Caloris basin (~330 to ~580 km from the basin center), it does not predict the observed radial graben of Pantheon Fossae near the basin center.

There are several aspects of this presumed pre-Apollodorus stress state that are important to consider. First, we did not address the extent to which faulting within the Caloris basin may have reduced the magnitude of stresses. Second, extensional stresses associated with uplift of the basin may have been induced by lower crustal flow (Watters et al., 2005; Kennedy et al., 2008) rather than an external annular load. And third, contraction associated with global cooling

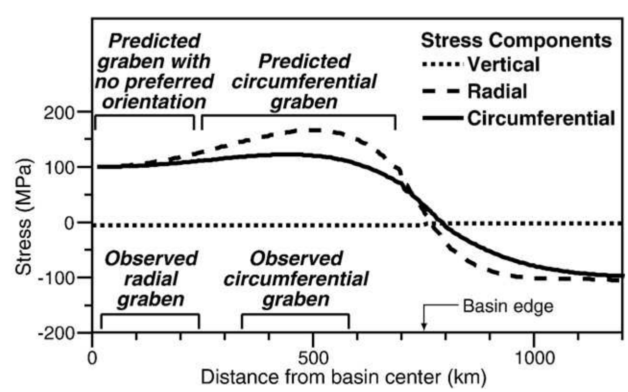

Fig. 3. Calculated principal stress components (from the model of Fig. 2C) near the surface, as functions of distance from the center of Caloris basin, associated with basin subsidence induced by interior fill followed by uplift induced by the emplacement of exterior smooth plains; a lithospheric thickness of 200 km is assumed. Regions of predicted circumferential graben are shown where the horizontal radial stress component is least compressive and the vertical stress component is most compressive. In the center of the basin, where the calculated horizontal radial and circumferential stresses are of similar magnitude, graben are not predicted to have a preferred orientation. Also shown are the locations of observed radial (Pantheon Fossae) and circumferential graben. Note that this stress state can predict faulting style but not whether such stresses are sufficient to induce faulting.

could have reduced the magnitude of extensional stresses. Nevertheless, we proceed with our relatively simple model of this pre-Apollodorus stress state and address whether the formation of the ~40-km-diameter Apollodorus crater could have altered this preexisting stress state sufficiently to induce the faulting in Pantheon Fossae.

4. Post-Apollodorus-impact stress state

Once the pre-Apollodorus stress state is established, we simulate the influence of the Apollodorus impact by reducing the elastic strength (initially 10^{11} Pa) within the ~40-km-diameter crater and a surrounding damaged region by a factor of 5 (factors between 3 and 10 lead to similar results). Here the term elastic strength denotes the relative quantity of elastic strain accommodated by a set of elements. In this context, reducing elastic strength means that these elements will accommodate proportionally more strain, in simulation of a pervasively fractured, low-strength region. Though we do not consider plastic rheologies in these calculations, reducing the elastic strength simulates significant fracturing of the basin fill such that the ability to support pre-impact extensional stresses is greatly reduced. This reduction causes the basin fill surrounding the Apollodorus crater to move radially outward away from the basin center, resulting in a reduction of radial extensional stresses. This outward movement also causes an increase in basin circumferential stresses. The combination of a radial stress decrease and circumferential stress increase creates a stress state conducive to the formation of radial graben, in a manner consistent with the formation of the Pantheon Fossae complex.

In the results described below, we calculate the relationship between the stress changes induced by the Apollodorus impact and assumptions regarding the extent of the impact damage zone, the thickness of lithosphere, the relative strength of basin fill versus the surrounding volume of Mercury's crust, and the magnitude of pre-Apollodorus basin uplift.

4.1. Influence of the extent of the Apollodorus impact damage zone

The radial extent of the zone of shock- and fracture-induced damage imparted to the volcanic fill within the Caloris basin by the Apollodorus impact is unknown. The damage zone is sensitive not only to strength parameters of the volcanic rocks, but also to the assumed strain that is required to fracture the rock (G. S. Collins, personal communication, 2008), neither of which is well constrained. There are, however, a variety of impact damage studies upon which we can draw size estimates. Senft and Stewart (2007) used a shock physics code to reproduce final crater shapes and damage zones from laboratory to planetary scales. They found that the depth to the base of the damage zone is ~1/4 the final crater diameter, a result in qualitative agreement with data from terrestrial craters (Ahrens et al., 2001). For the 40-km-diameter Apollodorus crater, that scaling would imply a damage zone of about 10 km in vertical thickness.

Geologic observations associated with the El'gygytgyn impact crater (18 km radius) in Russia show a damage zone (marked by extensive faulting) that extends to ~2.7 crater radii (Gurov et al., 2007). Similar results have been inferred for the extent of a damage zone surrounding the 23-km-diameter Haughton crater in Canada and the 25-km-diameter Ries crater in Germany (Collins et al., 2008). Moreover, numerical simulations of impacts and associated damage suggest that a 10-km-diameter impact crater should induce a damage zone to at least 15 km radial distance (Collins et al., 2004). These study results imply that the radial extent of damage near the surface is a factor of ~2–3 greater than the final crater radius. If this relationship holds for a similar-size impact into volcanic plains on Mercury, one may expect that the damage zone surrounding the ~20-km-radius Apollodorus crater within the Caloris basin could extend to a radial distance of as much as 60 km.

The uncertainty in the extent of the damage zone associated with the Apollodorus crater leads us to consider several potential damage zone geometries (Fig. 4A, upper inset). As we are modeling the damage zone with a rectangular cross-section when it is more likely bowl-shaped, the models likely overestimate the stress release in the outer reaches of this zone. In one end-member model, the damage zone is confined to within the Apollodorus crater itself, with a 20-km radius and a 3-km depth (damage zone I in Fig. 4A). The other end-member model consists of a damage zone that extends to a radial distance of 60 km and a depth of 10 km (damage zone IV). Fig. 4A shows how the extent of the damage zone influences the magnitude of the stress change from the pre-Apollodorus stress state. The minimum damage zone model (I) leads to a decrease in radial extensional stress and an increase in circumferential extensional stress out to ~50 km from the basin center. In contrast, the maximum damage zone model (IV) leads to stress changes that extend more than 200 km from the basin center. As the graben of Pantheon Fossae extend to a radial distance of at least ~230 km, the damage zone model most consistent with observations is the largest considered here, and a radial extent of a damage zone greater than 60 km would provide an improved fit.

4.2. Influence of lithospheric thickness

In the Kennedy et al. (2008) study, lithospheric thickness was difficult to constrain solely on the basis of observations of faulting within the Caloris basin. Models with both a relatively thin (60 km) and thick (200 km) lithosphere could explain Mariner 10 observations of graben to a distance of ~470 km from the basin center. Now that MESSENGER has revealed that circumferential graben extend to a radial distance of ~580 km (Murchie et al., 2008; Watters et al., 2009-this issue), the thicker-lithosphere models (100 to 200 km thickness) appear to be more appropriate, as such models lead to a broader flexural response to external loading. A broader flexural response causes significant differential stresses to extend farther from the center of Caloris basin. The thickness of the lithosphere prior to the Apollodorus impact cannot be further constrained, as the magnitude of differential stress required to induce faulting is not known.

The thickness of Mercury's lithosphere at the time of the Apollodorus impact and the formation of Pantheon Fossae, for the scenario considered here, is also difficult to constrain. For damage zone model IV, Fig. 4B shows how modifying the thickness of the lithosphere influences the stress changes induced by the Apollodorus impact. The thicker the lithosphere, the broader the reach of these stress changes from the basin center, but the differences among the models are not large. The broad expanse of Pantheon Fossae suggests that a thicker-lithosphere model may be the most appropriate.

4.3. Contrast in strength

The contrast in the elastic strength between the volcanic fill within the Caloris basin and the underlying and surrounding crust strongly influences the distribution of flexural stresses associated with surface loads. Though the relative elastic strength of crust and volcanic fill is not known, it is plausible that the volcanic fill, more recently emplaced, may be substantially stronger than the surrounding crust, which was likely significantly damaged by the Caloris basin-forming impact. Magmatic infilling of fractures beneath the basin floor, as has been inferred from gravity anomalies over older lunar craters (Dvorak and Phillips, 1978), would add additional strength to the upper regions of the basin relative to the surrounding crust. If the elastic strength of both rock types is similar, then the distribution of flexural stresses will vary smoothly and will be related closely to the flexural displacement of the lithosphere. However, if the basin fill is stronger throughout than the crust, then stresses could be substantially higher within the fill. As we attempt to understand the great extent of Pantheon Fossae, factors that tend to concentrate higher stresses in

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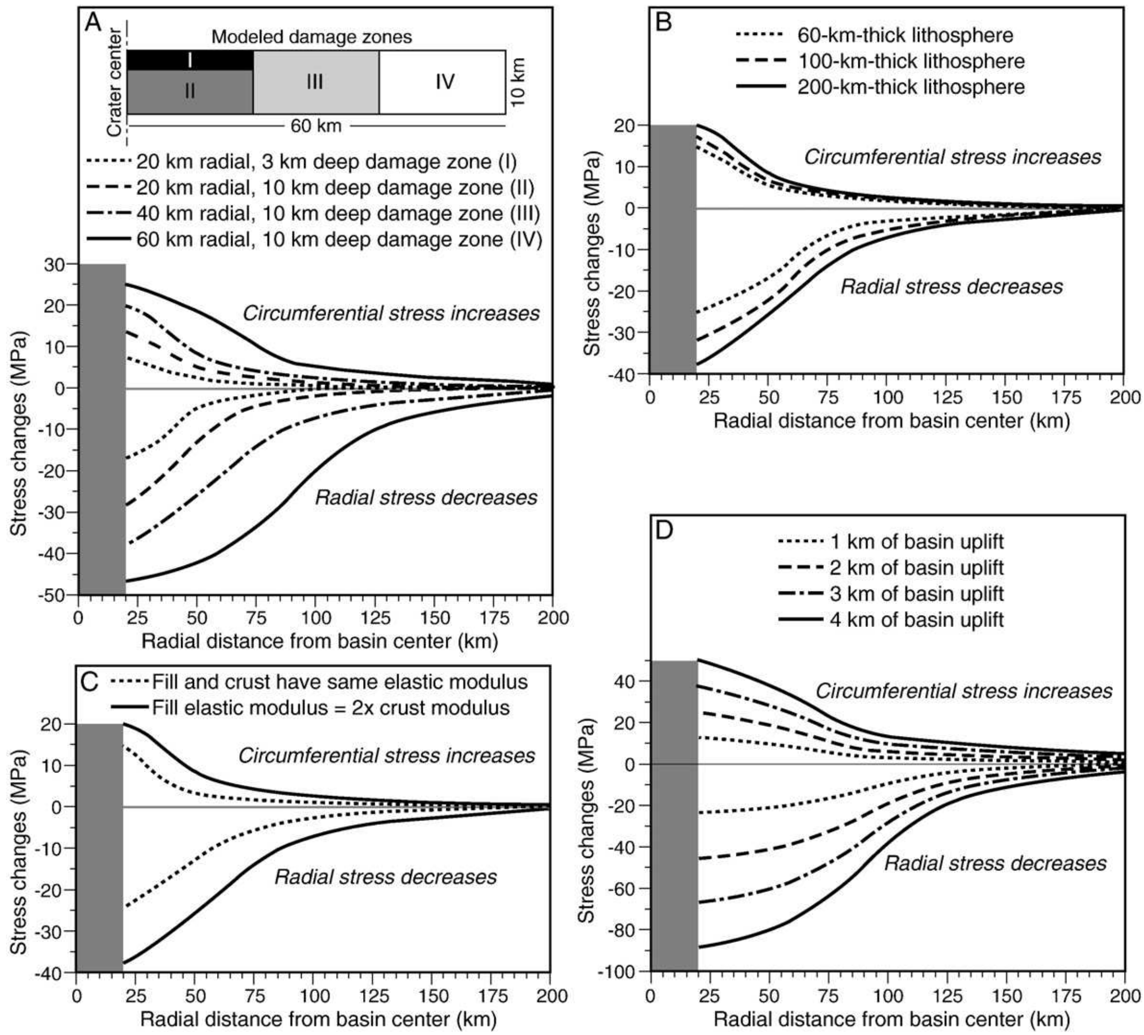

Fig. 4. Calculated increases in horizontal circumferential stress and decreases in radial stress as functions of radial distance from the center of the Caloris basin for a range of assumptions. (A) For different models of the damage zone (top illustration) induced by the Apollodorus impact. All damage zones shown in the upper inset extend outward from the crater center, which corresponds to the Caloris basin center. Models shown are for a pre-Apollodorus uplift of 2 km and a lithospheric thickness of 200 km. (B) For several values of lithospheric thickness. Models shown are for a damage zone with a radius of 40 km and a depth extent of 10 km. (C) For two assumptions regarding the relative elastic strength between the basin fill and surrounding crustal material. Models shown are for a damage zone with a radius of 40 km and a depth extent of 10 km and a 200-km-thick lithosphere. (D) For different assumptions regarding average basin uplift prior to the Apollodorus impact. Models shown are for a damage zone with a radius of 60 km and a depth extent of 10 km and a 200-km-thick lithosphere. In all four panels, stress changes are not shown for the innermost 20 km (gray region), the location of the breccia-filled Apollodorus crater floor, where pre-impact stresses were relieved by the impact.

the basin fill and thus enable higher stress release by the Apollodorus impact, may be important.

Fig. 4C shows how stress changes in the basin fill associated with the Apollodorus impact (for damage zone model IV) vary with the elastic strength of the pre-damaged basin fill relative to that of the surrounding crust. For fill having twice the strength of the surrounding crust, there is more than a 50% increase in the magnitude and extent of radial stress decreases and circumferential stress increases. The broad extent of Pantheon Fossae may thus argue for fill that is considerably stronger than the surrounding crust.

4.4. Influence of the magnitude of pre-Apollodorus basin uplift

The magnitude of the pre-Apollodorus stress state depends critically on the extent of subsidence and uplift preceding crater formation. Our analysis of initial subsidence is based on the assumption that compressional stresses in the uppermost kilometer of the basin fill are associated with subsidence only of this upper layer. Knowledge of the total thickness of basin fill is thus not needed. But the calculation for extensional stresses associated with uplift requires knowledge of the full extent of later exterior loading, which is not yet well constrained. Not only are the thicknesses of exterior smooth plains units poorly known, but MESSENGER color observations and the distribution of tectonic features have been interpreted to suggest that whereas volcanic plains are widespread in the eastern annulus they may be less extensive in the western annulus (Watters et al., 2009-this issue). Thus, loading may be non-symmetric.

Here we explore how the magnitude of external-loading-induced uplift and the symmetry of the annular load would influence the stress changes produced by the Apollodorus impact. Fig. 4D shows how circumferential stress increases and radial stress decreases vary as functions of basin uplift (for damage model IV). The relationship is linear, with stress changes directly proportional to the magnitude of uplift. A model with significant uplift is probably required to explain the broad extent of Pantheon Fossae, though the differential stress change required to induce the observed faulting is not well constrained.

Fig. 5A shows the displacement associated with the emplacement of external smooth plains only in the eastern annulus. This load geometry results in a very asymmetric uplift of the Caloris basin,

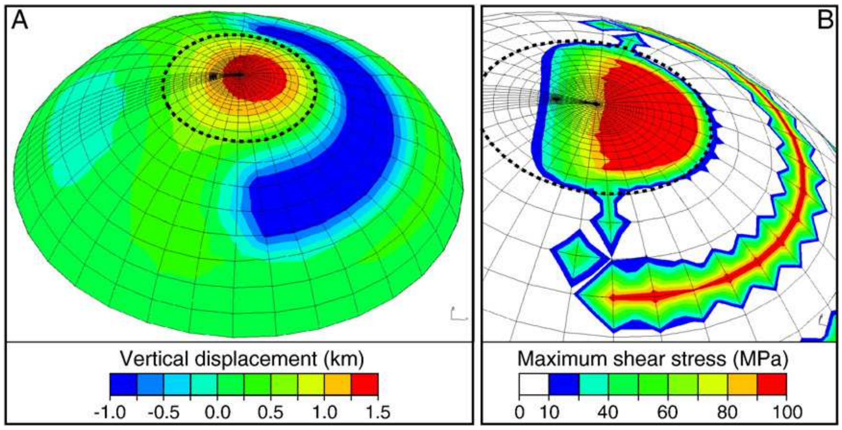

Fig. 5. (A) Vertical (radial to planet center) displacement associated with external smooth plains emplaced only to the east of Caloris basin. (B) Maximum shear stress at the surface due to this loading. The edge of the Caloris basin is shown by the dashed line.

which is reflected by an asymmetric maximum shear stress at the surface of the basin fill (Fig. 5B). Such a model is not likely to lead to the observed symmetry in circumferential graben around the outer regions of the basin, nor to the symmetry of the radial graben of Pantheon Fossae (Fig. 1). Thus, if further observations by MESSENGER indicate that external smooth plains loading is significantly greater in the eastern annulus than to the west, it is unlikely that the scenario explored here that Pantheon Fossae are the result of the Apollodorus impact is tenable. This does not rule out the scenario completely, but another more symmetric source of pre-Apollodorus uplift must be invoked, such as lower crustal flow following the Caloris impact (Watters et al., 2005; Kennedy et al., 2008).

4.5. Net post-Apollodorus stress state

If we invoke an Apollodorus impact model that induces significant stress changes to the Caloris fill (damage zone model IV, 200-km-thick lithosphere, elastically stronger fill, 2 km of basin uplift), and these stress changes are superimposed on the pre-Apollodorus stress state, we resolve a net stress state such as that shown in Fig. 6. Horizontal stresses near the center of Caloris basin are no longer of similar magnitude, but circumferential extensional stresses instead dominate, resulting in the prediction of radial graben consistent with the Pantheon Fossae complex. The model can account for both the radial graben emanating from the center of the Caloris basin and the circumferential graben observed in the outer regions.

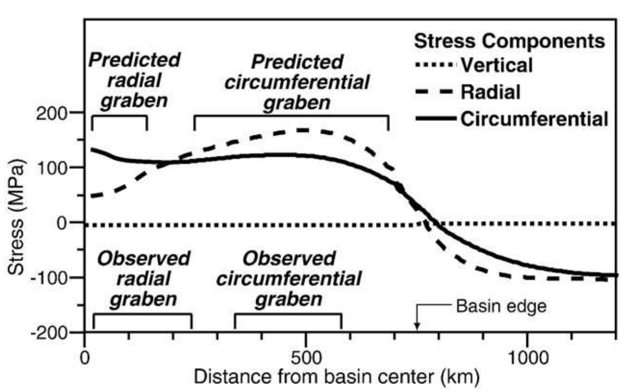

Fig. 6. Calculated principal stress components near the surface as functions of distance from the center of Caloris basin associated with basin subsidence due to interior fill followed by uplift due to the emplacement of the exterior smooth plains and following the Apollodorus impact. Regions of predicted radial and circumferential graben are shown where the horizontal circumferential and radial stress components are the least compressive stress, respectfully. Also shown are the locations of observed radial (Pantheon Fossae) and circumferential graben.

We note that the regions of predicted radial and circumferential graben do not correspond precisely to what is observed. Considering the simplicity of our models, however, and such unknowns as the magnitude and distribution of stress relief due to prior faulting, as well as the magnitude of differential stress required to fail in extension within the Caloris fill, our model results appear to match reasonably well the fault pattern seen in the basin. One of the most difficult aspects of Pantheon Fossae to explain with our modeling approach is the great radial extent of these features (to at least ~230 km). An improved fit to the radial extent of basin-radial graben could potentially be obtained with a broader uplift than considered here, a lithosphere thicker than 200 km, a greater radial extent of the damage zone, or greater contrast in elastic strength between the fill and the surrounding crust. Another possibility is that, once initiated, the faults may have been self-propagating, enabling radial graben to extend beyond the point that would normally be predicted by the stress state at the time of the impact.

4.6. Importance of the location of the Apollodorus impact

If the Apollodorus impact and its associated damage induced the radial graben of Pantheon Fossae, it is reasonable to ask how important it is that the Apollodorus crater be located very near the center of the Caloris basin. There are, for instance, several other craters comparable in size to the Apollodorus crater that are located 200 km or more from the basin center that did not apparently lead to the formation of graben radiating outward from their rims (see Fig. 1 of Murchie et al., 2008).

To understand the importance of the location of the Apollodorus crater, we moved the location of the modeled crater 200 km to the west (black circle in Fig. 2B). Fig. 7 shows that calculated maximum shear stresses induced by the original versus the modified crater locations are nearly identical. This similarity is also true for the decrease in radial stress and increase in circumferential stress. This result does not change dramatically as long as the impact crater is within about 600 km of the basin center, beyond which induced stress changes diminish rapidly as flexural stresses from external loading decrease sharply beyond this location. What differs is the superposition of these impact-induced stress changes relative to the distribution of pre-existing extensional stresses. As was shown in Fig. 3, pre-existing radial and circumferential stresses are identical at the basin center and begin to diverge (with radial stresses becoming larger) only about 300 km from the basin center, eventually leading to circumferential graben at a radial distance of 330 km. Had the Apollodorus impact occurred outside of about 300-km radial distance from the basin center, the stress changes would not be sufficient to

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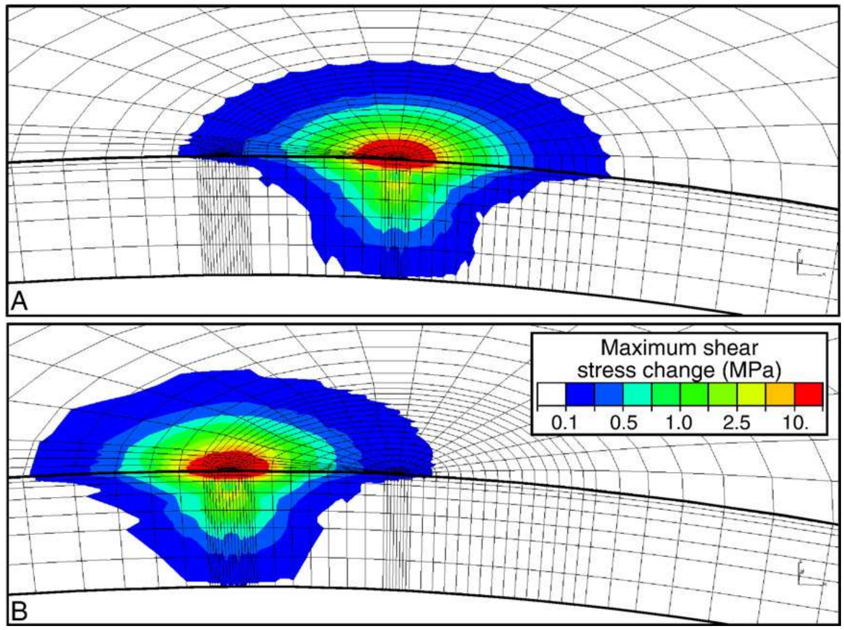

Fig. 7. Maximum shear stress change due to the (A) Apollodorus impact at the center of Caloris basin and (B) a similar impact located 200 km from the basin center.

cause the circumferential stresses to be most extensional, and radial graben would not be predicted.

These results suggest that any of the other moderate-size impacts that occurred within the central zone of the Caloris basin could have initiated a structure similar to Pantheon Fossae. That they did not suggests either that the premise underlying our modeling is incorrect, or that the similar-sized impacts occurred at a time when the stress state within the Caloris basin was not strongly extensional. Faulting associated with Pantheon Fossae may have already relieved much of the extensional stress, or the growth of compressional stresses associated with global contraction may have negated the extensional stress field. The applicability of these two ideas depends on whether Apollodorus is older than other comparably large craters in the central Caloris basin region. The closest crater comparable to Apollodorus is Cunningham, 37 km in diameter and about 210 km west of Apollodorus. The freshness of the crater and the extensive system of bright rays of ejecta radiating from it suggest that Cunningham is Kuiperian in age (less than about 1 Ga (Spudis and Guest, 1988)) and substantially younger than Apollodorus. A still larger crater in central Caloris is Atget, 100 km in diameter and about 250 km to the southeast of Apollodorus. The Atget impact, as that of Apollodorus, is younger than the Caloris interior smooth plains (Murchie et al., 2008; Watters et al., 2009-this issue) and excavated low-reflectance material from beneath those plains deposits. Ejecta from Atget appear to overlie and truncate troughs from the Pantheon Fossae complex and would therefore be younger than the graben complex, but the relative age of Atget and Apollodorus are otherwise difficult to ascertain. These relationships are not inconsistent with a special role for Apollodorus as a trigger for the release of extensional stress in the Caloris basin interior, but additional analysis of the chronology of crater formation on the basin interior plains is warranted to test this inference further.

5. Summary

MESSENGER's discovery of the Pantheon Fossae complex near the center of the Caloris basin was one of the highlights of the spacecraft's first Mercury flyby. The finding that the radial graben of the complex extend outward from the relatively small Apollodorus crater raised the question of whether the two structures are related. Here we use a series of 3-D viscoelastic finite element models to describe a scenario whereby the Apollodorus impact induced a change to a pre-existing stress state, generating Pantheon Fossae. Under this idea, a pre-existing stress state resulting from early basin subsidence followed by later uplift left the surface of the Caloris basin in a state of net extension. Evidence for this extensional state is the existence of circumferentially oriented graben throughout the outer regions of the basin. As horizontal radial and circumferential stresses near the center of the Caloris basin are calculated to be nearly equal in magnitude, there was no preferred orientation of extensional features near the basin center.

By this scenario, the impact – which produced the ~40-km-diameter crater and potentially a much larger damage zone – modified this stress state essentially instantaneously. By reducing the ability of the volcanic fill to support elastic stresses throughout the damaged area, the impact caused fill material to move radially outward. This movement caused a decrease in radial stress and an increase in circumferential stress conducive to the formation of the radial graben that make up the Pantheon Fossae complex. As the stress changes would have traveled at seismic wave speeds and the faulting could have progressed at rupture propagation speeds (both measured in kilometers per second), ejecta from the Apollodorus impact transported ballistically outward from the crater could still be deposited after the graben had largely formed, as is observed (Murchie et al., 2008).

Whether this scenario could provide significant stress changes out to ~230 km or more from the basin center, the extent of Pantheon Fossae, is not known, since the magnitude of differential stress required to form graben 100 to 200 m deep (Watters et al., 2005) is poorly constrained. Broader stress changes associated with the Apollodorus impact are generated with a greater initial extensional stress state (i.e., a greater pre-Apollodorus uplift), a broader damage zone, a stronger basin fill relative to surrounding crust, and a thicker lithosphere. Once initiated, self-propagating faulting may have also increased the radial extent of Pantheon Fossae beyond where models predict significant impact-induced changes to stress.

Our models also suggest that the location of the Apollodorus crater, and therefore Pantheon Fossae, very near the center of the Caloris basin, is coincidental. A similar complex of radial graben could have been generated from a similar-sized impact anywhere within about 300 km of the Caloris basin center. The fact that no other similar-sized impacts induced such a complex implies either that no significant extensional pre-stress was present at the times of those impacts, or

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our scenario linking Apollodorus and Pantheon Fossae is not correct. We also find that the symmetry of both the Pantheon Fossae complex and the circumferential graben in the outer reaches of the Caloris basin interior requires fairly symmetric external loading. If external loading is found to be asymmetric, then another source of pre-Apollodorus uplift (e.g., lower crustal flow) must be postulated in order for the scenario outlined here to explain the formation of Pantheon Fossae.

Future observations to be made by MESSENGER, particularly of topography and gravity, should help to constrain further the models used to calculate the pre-Apollodorus stress state. High-resolution imaging should also help to clarify the geometry of Pantheon Fossae, whether the complex is superposed on older faults, and the tectonic history of the Caloris basin more generally.

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