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Eros' Rahe Dorsum: Implications for internal structure

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Abstract–An intriguing discovery of the NEAR imaging and laser-ranging experiments was the ridge system known as Rahe Dorsum and its possible relation with global-scale internal structure. The curved path of the ridge over the surface roughly defines a plane cutting through Eros. Another lineament on the other side of Eros, Calisto Fossae, seems to lie nearly on the same plane. The NEAR teams interpret Rahe as the expression of a compressive fault (a plane of weakness), because portions are a scarp, which on Earth would be indicative of horizontal compression, where shear displacement along a dipping fault has thrust the portion of the lithosphere on one side of the fault up relative to the other side. However, given the different geometry of Eros, a scarp may not have the same relationship to underlying structure as it does on Earth. The plane through Eros runs nearly parallel to, and just below, the surface facet adjacent to Rahe Dorsum. The plane then continues lengthwise through the elongated body, a surprising geometry for a plane of weakness on a battered body. Moreover, an assessment of the topography of Rahe Dorsum indicates that it is not consistent with displacement on the Rahe plane. Rather, the topography suggests that Rahe Dorsum results from resistance of the Rahe plane to impact erosion. Such a plane of strength might have formed in Eros' parent body by a fluid intrusion (e.g., a dike of partial melt) through undifferentiated material, creating a vein of stronger rock. Albedo, color and near-infrared spectra could be consistent with a distinct material composition and such a history, although the instruments' resolution was not adequate for a definitive detection of such a spatially limited component. However the plane of strength formed, such structural reinforcing might have enabled and controlled the elongated irregular shape of Eros, as well as Rahe Dorsum.

INTRODUCTION

One of the most remarkable discoveries by the NEAR mission to asteroid Eros was the ridge named Rahe Dorsum. As viewed from most directions, the ridge traces a curved path over the surface of the irregularly shaped body (Figs. 1 and 2). However, the science team for the NEAR multispectral imager (MSI) insightfully noted that the path actually lies close to the intersection of a plane with the surface (Veverka et al. 2000; Thomas et al. 2002a; Prockter et al. 2002; Robinson et al. 2002). Consequently, when viewed from a point on an extension of that plane into space, the ridge follows a nearly straight line (Fig. 3). The NEAR team also discovered another linear feature, a relatively short set of ridges and troughs called Calisto Fossae, on the opposite side of Eros lying nearly in the same plane defined by Rahe Dorsum (Fig. 4). This plane (called here the Rahe plane) appears to be a major structural feature of the body of Eros (Veverka et al. 2000; Thomas et al. 2002a; Prockter et al. 2002; Robinson et al. 2002).

The qualitative appearance of Rahe Dorsum led to a specific interpretation of the process that formed it, which was included in the first quick-look report by the NEAR imaging team (Veverka et al. 2000): "The morphology of the majority of the ridge is suggestive of compression." Subsequent reports elucidated that statement. Thomas et al. (2002a) reported that "the observed morphology is most characteristic of a shallow angle fault in which the hanging wall block has moved up relative to the footwall block." In other words, it appeared to those authors that the ridge resembled the appearance of thrust faults, which on Earth (and elsewhere) result from compression. A similar statement is made in the review by Robinson et al. (2002), who added the explicit implication that the internal plane defined by Rahe Dorsum and Calisto Fossae is the fault plane, and thus is a plane of weakness.

Only Prockter et al. (2002) included supporting evidence for the interpretation that Rahe is a thrust fault, a single image showing a view of a curving portion of the ridge, which suggests a scarp-like topography dropping downward from the concave

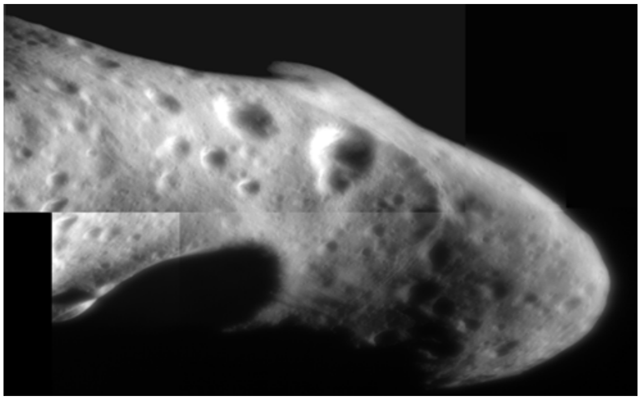


Fig. 1. A montage of NEAR images showing a portion of the ridge Rahe Dorsum, based on the same images used in Fig. 2a of Thomas et al. (2002), except that here I have retained a view of a much larger portion of Eros to help show the placement of Rahe Dorsum relative to the body of the asteroid. The enormous crater Himeros (11 km diameter) appears edge-on at the upper left. Rahe Dorsum crosses within Himeros (out of sight in this view) and emerges running toward the right and making a hook as in turns back toward the 5 km wide crater Psyche (lower left). After the hook, the ridge comes to an end a few kilometers short of reaching Psyche. The ridge passes tangent to the 2 km wide crater Tutanekai. (Tutanekai is readily identified by the kilometer-wide crater that interrupts Tutanekai's rim on the side opposite Rahe). Montage includes parts of images 129901617, 129901657, 129901697, 129901737, 129901777, 129901817, 129901857, and 129901897.

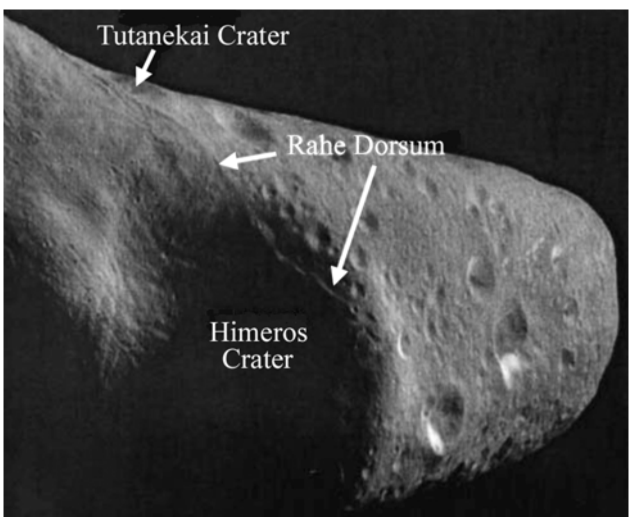


Fig. 2. A view of the side of Eros opposite that in Fig. 1. At the top Rahe Dorsum passes tangent to crater Tutanekai, which here appears nearly edge-on and beyond the ridge. Here we can see the ridge cross over the rim of Himeros and across an interior wall of the giant crater. The ridge ends at the lower right within Himeros. (Figure based on Fig. 3a of Prockter et al. 2002)

side of the curving ridge to the outside of the curve. In addition to the example displayed by Prockter et al., many other images seem to show that morphology (Fig. 5 is another example). Indeed, on terrestrial planets, such scarps are often indicative of thrust faults.

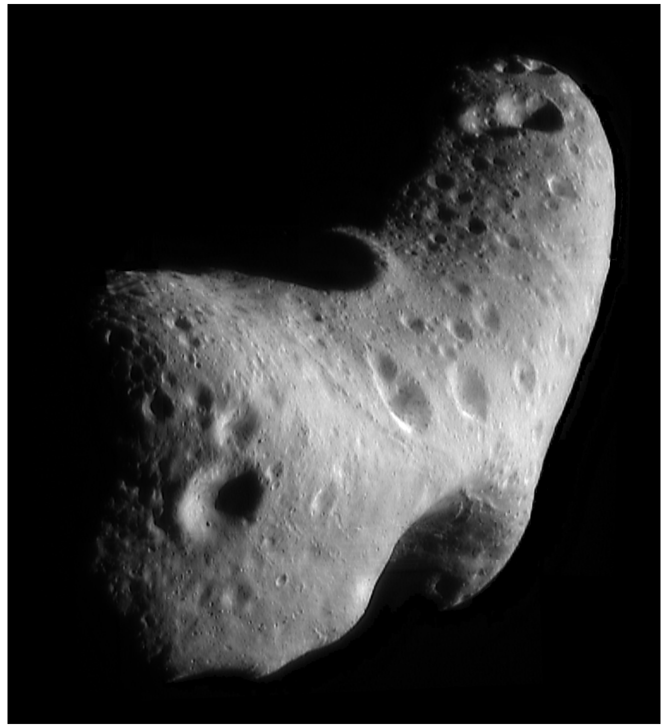


Fig. 3. The full extent of Rahe Dorsum is visible from this perspective (image PIA 02923). The ridge runs from within Himeros (at lower right) towards Psyche (crater at top center), passing by Tutanekai (the crater between Psyche and Himeros in this view). In this view, Rahe Dorsum is nearly straight. Even the hooked part (upper left of Tutanekai looks straight here, as does the path over the rim and within Himeros. Evidently the camera in this view lies in the extended Rahe plane.

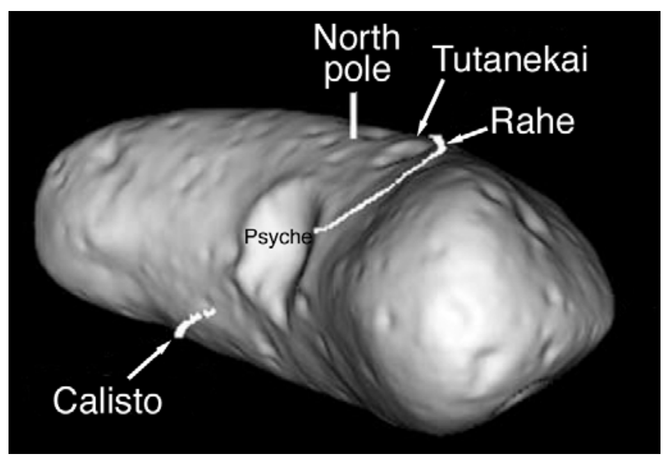


Fig. 4. An artificial view based on a shape model by Peter Thomas provides another perspective from a point near the extended Rahe plane (image based on Fig. 3 of Thomas et al. 2002). Compare the positions of Tutanekai and Psyche to Figs. 1, 2, and 3. Here the view is slightly off the plane so we can see the curve of the hooked part of Rahe Dorsum between where it passes Tutanekai and it approaches Psyche. Note that Thomas et al. indicate that Rahe Dorsum reaches Psyche, but in fact it peters out before it gets there. Also shown here is the position of Calisto Fossae, which can be seen to be near the same plane.

On the other hand, the appearance of the topography on Eros varies considerably with lighting conditions and viewing direction. Consequently, the scarp-like appearance is less pronounced, and even reversed, by the ridge's appearance in other images. Fortunately, the NEAR Laser Rangefinder (NLR) provides complementary information that is independent of the effects that make determination of topography from images so challenging. Some topographic profiles across Rahe Dorsum based on NLR data have been published (Cheng et al. 2002; Watters and Robinson 2003). However, the NLR data set is rich and extensive, and has not yet been fully exploited for investigating structural issues such as the character of Rahe Dorsum.

In this paper I assess the hypothesis that Rahe Dorsum is a compressive feature and that the internal plane defined by Rahe and Calisto is a plane of weakness. (For conciseness I will refer to this plane as the Rahe plane.) First I consider the traditional relationship between compression and the geometry of thrust faults on a terrestrial planet; whether it would be relevant on a small irregularly shaped body; and what topography would be indicative of fault displacement analogous to a thrust fault. Next I describe the placement of the Rahe plane within Eros, and discuss its orientation relative to the surface along the line of its intersection at Rahe Dorsum. Then, using NLR data, I examine the topography along Rahe Dorsum and compare it with expectations from the compressive thrust fault hypothesis. From this study, there does not appear to be a topographic signature indicative of shear displacement along the Rahe plane, whether a compressive thrust fault or due to any other cause; In fact, the evidence appears to be consistent with the Rahe plane being a surface of strength rather than of weakness.

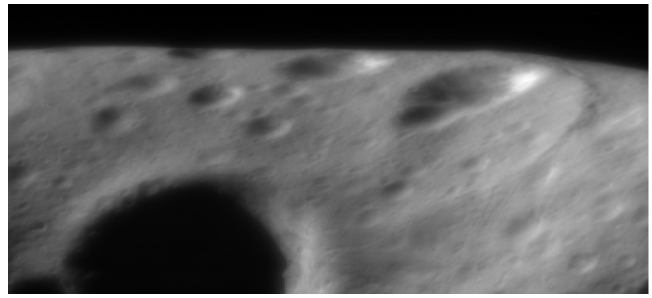


Fig. 5. One of many images taken by the NEAR camera with illumination of Rahe Dorsum that shows a scarp-like topography (image 129740425). The image shows (at upper right) the hooked portion of Rahe that runs from the point of tangency with Tutanekai crater to where the ridge approaches Psyche (the large crater at bottom left). The scarp-like topography is found along the part closest to Tutanekai, with the drop off toward the outside of the hook.

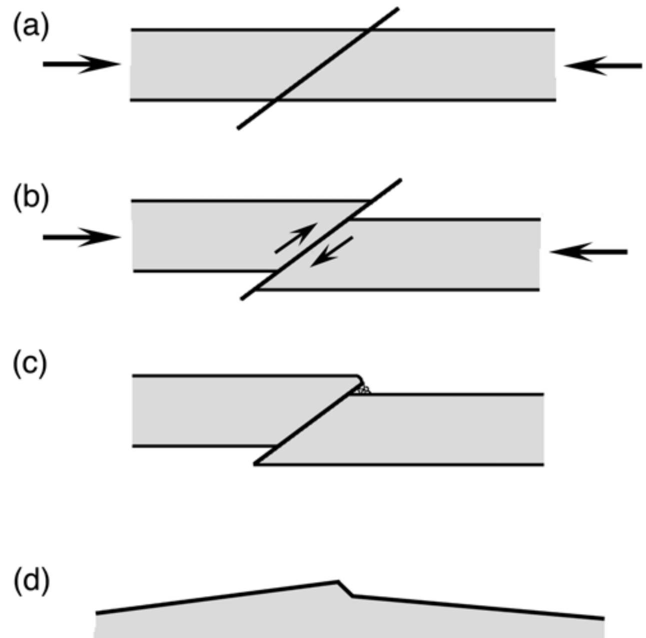


Fig. 6. A schematic of scarp formation. a) Horizontal compression in a planetary lithosphere can create a dipping fault if the material fails, or exploit a preexisting fault. b) The compression results in shear displacement along the fault. c) Local collapse at the surface removes an overhang and completes the formation of the scarp. The surface profiles on opposite sides (immediately left and right of the scarp) are parallel to one another. d) A scarp for which the surfaces on opposite sides (immediately left and right of the scarp) are not parallel would not be indicative of lateral compression, nor of thrust faulting, nor of displacement along an interior plane.

THRUST FAULT GEOMETRY

The geometry of thrust faults was first understood on Earth, where examples are common, their surface manifestations can be examined in detail, and the underlying fault structure can be explored by geophysical techniques as well as at sites of fortuitous exposure (e.g., Davis and Reynolds 1996). Examples of thrust faults have also been recognized on the Moon, Mercury, and Mars (e.g., Glass 1982).

For a terrestrial planet, the traditionally understood relationship between the surface appearance of a topographic scarp, the underlying fault plane, and a compressive regime can be understood in the following way (Fig. 6). Horizontal compressive stress on the lithosphere (a) results in displacement (b) along an inclined ("dip-slip") fault, resulting in a raised elevation on one side of the fault relative to the other. Erosion or collapse generally eliminates the overhang that would be predicted by the simple geometry, and results in the final scarp (c).

Several points regarding this geometry are important if it is to be applied to an irregularly shaped body. First, the displacement along the fault plane is in shear. This shear is driven by compression in a lithosphere of a planet large enough that over the region in question, the material involved is essentially a flat brittle layer. Thus, on an irregular body, a scarp may indicate shear displacement along a plane that intersects the surface, but the geometry that usually associates such topography with compression only applies on a large planet with a lithosphere. Accordingly, on Eros, even if a scarp indicated displacement on an underlying fault, it is not clear how such displacement could be driven by compression. The association of scarps with compressionally driven thrust faults was originally based on experience with large spherical planets with lithospheres, and is probably not relevant for Eros.

Another important point follows from the basic geometry of shear displacement on a plane that intersects the surface of the body, whether driven by compressional thrust or some other force. The topography at a scarp is only indicative of shear along the inclined fault if the profile of the surface on the raised side of the fault is parallel to the profile on the lowered side (as in Figs. 6b and 6c). More precisely, the tangent to the surface on either side of the fault must be parallel. A scarp with a profile like the one in Fig. 6d would not necessarily be indicative of shear displacement on a dipping fault, because the profiles on opposite sides of the scarp (immediately to the left and right of the scarp in Fig. 6d) are not parallel. For this reason, as shown in the Surface Profiles section, even where Rahe Dorsum has a scarp-like profile, it is not indicative of displacement along a fault.

GLOBAL PLACEMENT OF THE INTERNAL RAHE PLANE

In order to grasp the nature of the Rahe plane, it is helpful to consider the appearance of the ridge from various perspectives and to view its orientation relative to Eros' figure. In general form, Eros resembles the shape of a ballet pointe shoe. This shape is most evident as viewed from the rotational poles, which define the latitude and longitude coordinate system. Figure 7 shows a synthetic view looking along the axis at the north side, with images reprojected by Bussey et al. (2002). The toe of the shoe is at the left, the heel is to the right, and the arch is at the bottom. The 5-kilometer-wide crater Psyche is prominent in the arch, and is viewed nearly edge-on from this point of view. Here I have indicated the path of Rahe Dorsum over the surface with a bold, black line. The ridge starts in the large crater Himeros near the top (the instep of the shoe), it crosses over the rim of Himeros, then passes tangent to the rim of crater Tutanekai. In this image, Tutanekai lies just below the mid-point of the path of the ridge. The ridge continues past Tutanekai, hooking back toward the center of Psyche.

The same features are viewed from different perspectives in previous figures. Figure 1 shows a view similar to that in Fig. 7, although seen from a point somewhat to the lower left relative to Fig. 7. From the point of view in Fig. 1, both Himeros (top left) and Psyche (bottom left) are seen nearly edge-on with their interiors in darkness that continues into the sky. In Fig. 1, we see the ridge emerging from Himeros at the top, passing Tutanekai, and hooking around toward Psyche. The ridges comes to an end at a point about one Psyche-radius before the rim of Psyche. Note the near tangential relationship of the ridge with Tutanekai. Tutanekai is distinguished and recognizable by the smaller (about half its radius) crater that intersects its rim on the side opposite Rahe Dorsum.

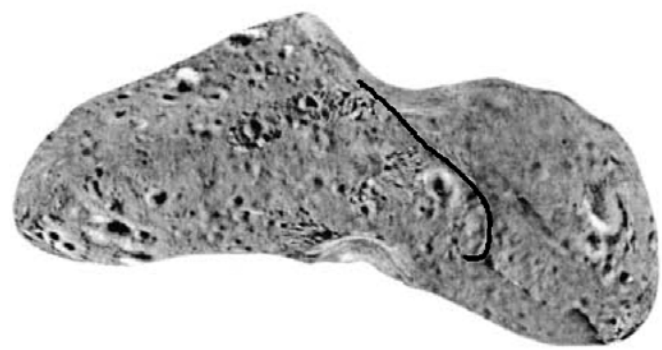


Fig. 7. An artificial view of Eros from a point along the north spin axis, created by Bussey et al. (2002) by projecting various images of portions of the surfaces onto a shape model of the asteroid. The trajectory of Rahe Dorsum from within Himeros (top), past Tutanekai, and hooking back toward Psyche, is marked here by a bold black line. This map helps place Figs. 1–5 in their global context and mutual relationships. By conventional definition, longitude zero is to the right, so for example the heel of the shoe (lower right) is at about 25°W.

The distinctive pattern of Tutanekai and its relationship with Rahe Dorsum is useful for orienting images taken from a variety of perspectives. For example, Fig. 2 shows the portion of the ridge within Himeros, continuing out over the rim and past Tutanekai. In this view, Tutanekai appears on the far side of the ridge, while in Fig. 1 it appeared on the near side.

In Fig. 3, we are looking nearly lengthwise along the ballet shoe, with its heel to the left, its toe to the right in the distance, and its arch upwards with Psyche in the middle. At the lower right we can see into Himeros. In the center, and just to the upper right of Rahe Dorsum, is the distinctive form of Tutanekai. Here we see the full length of Rahe Dorsum from the interior of Himeros, over the rim, across past Tutanekai, and heading toward Psyche. At the time this image was taken, the NEAR spacecraft was evidently in (or very nearly in) the extended Rahe plane, which is why the ridge appears nearly straight.

The highly curved, hooked portion (cf. Fig. 1) appears here as a straight line between Tutanekai and the left side of Psyche. The area enclosed within the hook (cf. Fig. 1 for example), appears highly foreshortened in Fig. 3. In fact, this portion of the surface lies very close to the Rahe plane, as shown by image-based shape models described below and by NLR topographic information (section Surface Profiles). The appearance of the area within the hook in Fig. 5 also gives a sense of its closeness to the plane defined by the curved part of the ridge.

The synthetic view by Thomas et al. (2002a) in Fig. 4 (based on their extremely useful shape model) also suggests that the Rahe plane lies close to the surface in this region within the hook. For orientation of Fig. 4 relative to the other images, note the indicated location of the ridge passing tangent to Tutanekai at the upper right. We are looking almost straight down at the heel of the shoe (bright area to the lower right of center), with the toe at the left, and Psyche in the center of the arch. In the perspective shown here, we are just far enough off the Rahe plane that the curve of the hook of Rahe Dorsum is visible between Tutanekai and Psyche, but we are close enough to the plane that we can confirm that the area within the hook appears to lie close to the plane as well. (Note that Thomas et al. (2002a) marked in this synthetic image the extension of the Rahe plane all the way to the rim of Psyche, but in fact the ridge itself terminates well outside Psyche as described above (Figs. 1, 3, and 5).

A more complete understanding of the relationship of the Rahe plane can be obtained by viewing a physical three-dimensional model of Eros (developed by P. Thomas, based on a quantitative shape determination [Thomas et al. 2002b]) from various perspectives viewed along the plane (Fig. 8). The parts of Fig. 8, from a to f, show views increasingly westward relative to the conventional coordinate system. Near the middle of the sequence, Fig. 8c shows a view similar to Fig. 4, including Rahe Dorsum from where it passes Tutanekai, through its hooked portion, to its terminus where it approaches Psyche. A portion of Calisto Fossae is also visible from this point of view. Here the hook appears edge-on as a nearly straight line, which is aligned with Calisto Fossae. Hence this viewpoint (in Fig. 8c) lies even closer to the Rahe plane than the synthetic view in Fig. 4.

Next consider the view from further to the right relative to Fig. 8c, that is in Fig. 8b and even further to the right in Fig. 8a. In each of these images the point of view continues to lie in the Rahe plane, so that the track of the ridge remains straight all the way to its terminus within Himeros (the right end of the path in Fig. 8b and 8a.) Because we are looking along the plane, the hook appears as a nearly straight line in Figs. 8a–c. From any other perspective than the Rahe plane, the path to the right of the hook would appear very wiggly, as it traverses the extreme topography crossing over Himeros' rim and across its inner wall.

Figure 8e shows how close the surface of Eros inside the curve of the Rahe hook lies to the Rahe plane. This area appears on the "limb"[1] of Eros in Fig. 8e to the right just above the line marking the Rahe plane. Here we can see the small angle of this part of the surface relative to the Rahe plane (<8°).

To complete the picture of the orientation of the Rahe plane relative to the surface, as well as confirm the important relationship with the location of Calisto Fossae discovered by the NEAR team, consider the view moving leftward (roughly westward) from the view in Fig. 8c. West of Fig. 8c, Fig. 8d shows the hook end of Rahe Dorsum to the right, the approximate alignment of Calisto with the Rahe plane, and the crossing of the plane through Psyche crater. Note that Calisto Fossae, while located on the plane defined by Rahe Dorsum, is angled slightly relative to the plane (Figs. 8e and 8f). If Calisto is indeed an expression of the intersection of the Rahe plane with the surface, then the Rahe plane is not a perfect plane. This result is confirmed in the next section where the NLR global topography data are considered.

NLR RESULTS AND THE CHARACTER OF THE RIDGE

The NEAR Laser Rangefinder produced a remarkable data set that can be brought to bear on the characterization of the ridge system and its relation to the global figure. One particularly useful and accessible product is the detailed shape of the asteroid in spherical coordinates (radius, latitude, and longitude). The surface is represented by a matrix that gives the radius values at points spaced uniformly 1/8° apart in latitude and longitude, presented with a radial precision of 0.25 m.

The NLR topography data is actually not that precise. Characterization of the uncertainty is complex, and depends on the spacecraft orbit during the measurements, instrument pointing, and integration of a network of ground tracks obtained from various distances and directions. In places, elevations may be off by ~10 m, and uncertainties in the position by a few times that much (Cheng et al. 2002). That precision is adequate for the characterization of the ridge topography for purposes of this paper. Moreover, the profiles derived here give consistent, similar results. We have also reproduced the high-precision single-track profiles of Cheng et al. (2002), confirming the validity of the NLR global radius matrix.

In principal this two-dimensional numerical array can be viewed as an image, with a gray scale assigned to represent radius values. However, the shape of Eros is so elongated and irregular that a wide range of grey values is needed to span the range of radii from 3020 m to 17,656 m. Thus more subtle features, like Rahe Dorsum, Calisto Fossae, and most craters each span too narrow a range of gray values to be recognizable. The locations of these features can be extracted from the image by various filtering techniques. Figure 9 shows the result of using an edge-recognition filter that clearly brings out the positions of Rahe and Calisto relative to the landmark craters and other features. It is useful to compare this automated representation with the interpretive map by Thomas et al. (2002a, their Fig. 1) drawn on the same projection. Of course, while Fig. 9 shows positions of features quite well, the grey scale is no longer correlated with radius values. For radius information the original numerical matrix must be used.

This projection shows that the interior surface defined by Rahe Dorsum and Calisto Fossae cannot be a perfect plane. If it were, geometry would require the point of its highest northern latitude to be at a longitude exactly 180° in longitude away from the point of furthest south latitude. In Fig. 9 we see that the farthest south point (near one end of Calisto Fossae) is at, or even west of, longitude 180°W (the left edge of the map). However, the farthest north point is east of Tutanekai near longitude 45°E. The longitudes of the farthest north and farthest south points are about 225° apart in longitude. Similar positions are shown on the map by Thomas et al. (2002a, Fig. 1).

[1]By "limb" I mean the edge of the model asteroid against the artificial sky background.

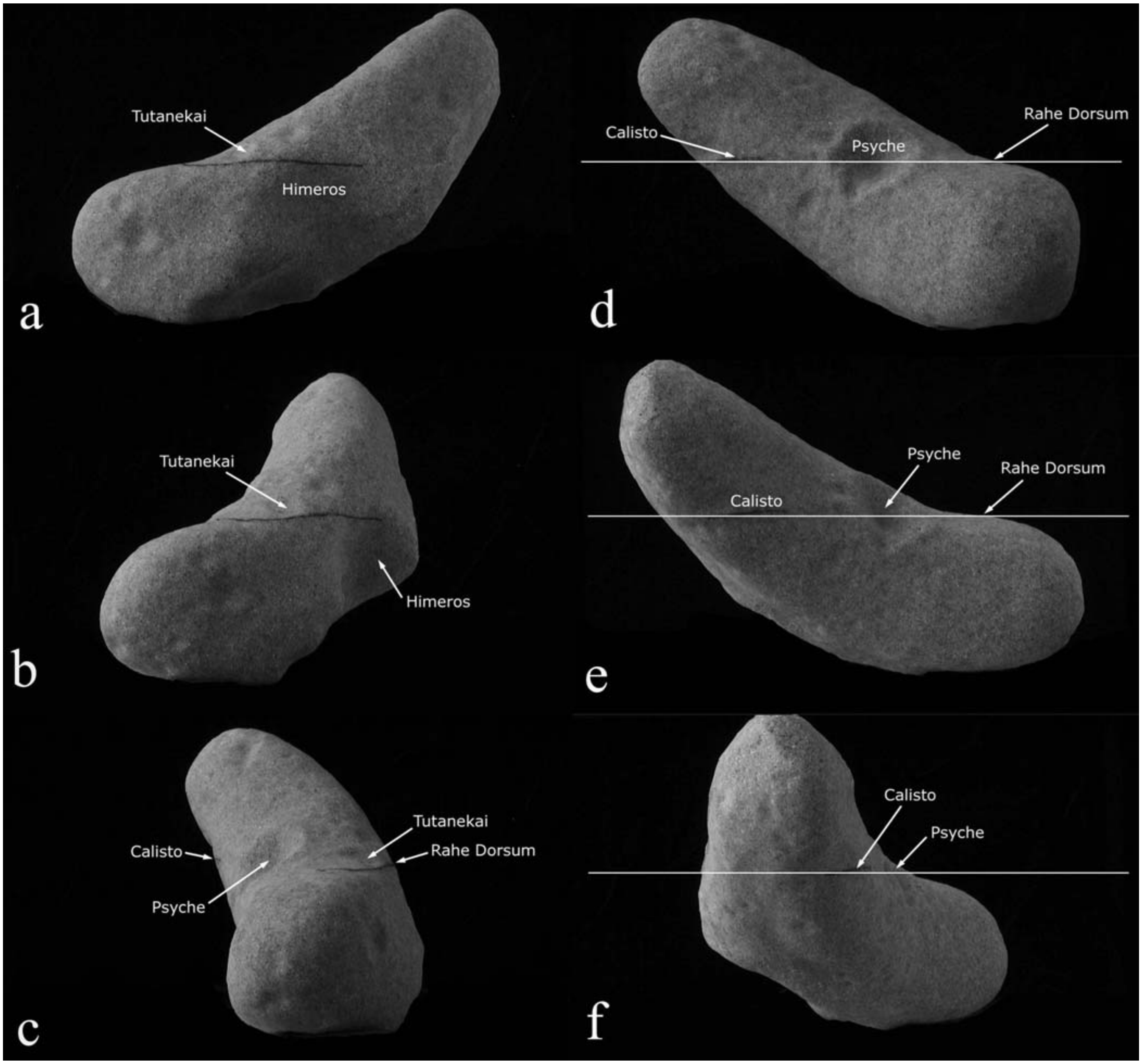
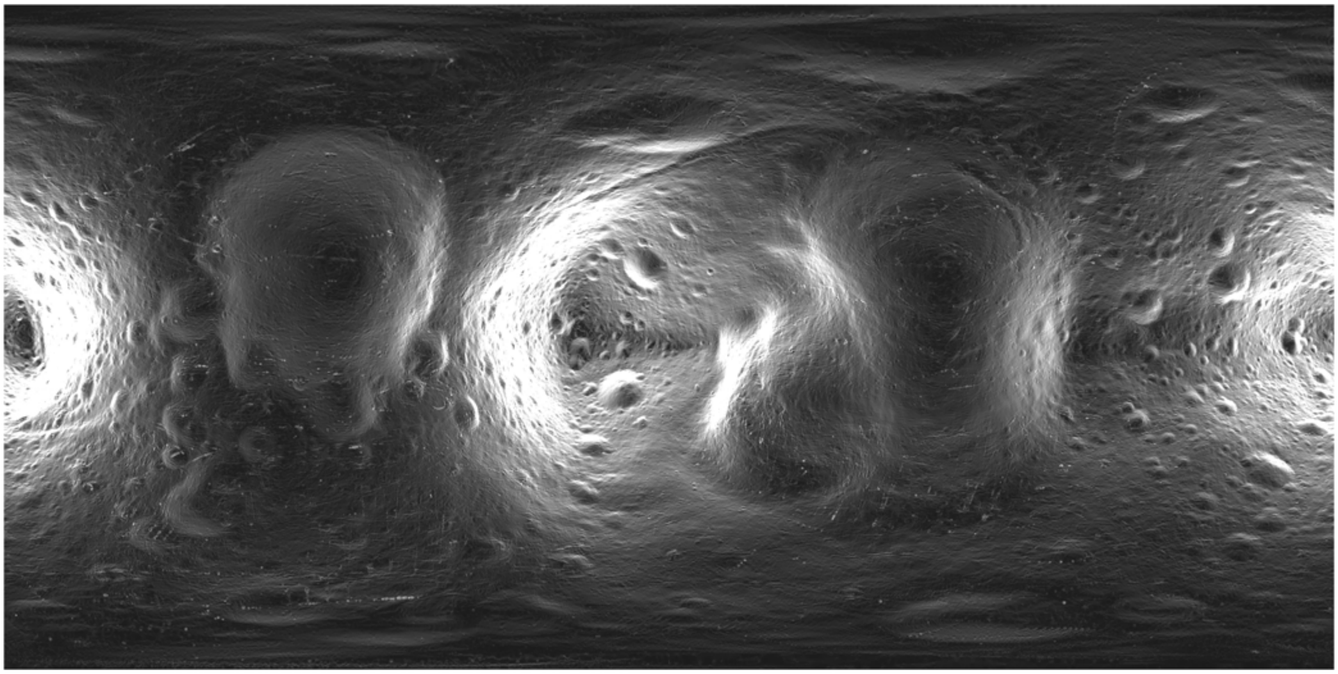


Fig. 8. A sequence of artificial views of Eros, constructed using P. Thomas' shape model. Each view is from a point lying on the extended Rahe plane, so that the Rahe plane is a straight line (shown as a white line in parts d–f). Accordingly, the intersection of the Rahe plane with the surface (e.g., along Rahe Dorsum) is a straight line in these views. North is roughly upward, although this orientation varies from frame to frame because the Rahe plane is somewhat oblique relative to the north-south axis. In the sequence from (a) to (f) the view moves increasingly toward the west. Part (a) shows the end of Rahe Dorsum in Himeros crater, and in part (f) the asteroid is rotated around past Calisto Fossae, which is located nearly on the Rahe plane. Rahe Dorsum and Calisto Fossae are marked by dark lines on the model.

Therefore the interior surface represented by Rahe and Calisto cannot be a plane. The required deviation from a plane is at least a slight twist (indeed Calisto Fossae has been described by the NEAR team as "the spiral feature southwest of Psyche," e.g., Cheng et al. 2002). In principle, deviation from a plane could be at odds with the shear displacement implicit in the NEAR teams' thrust-fault hypothesis. However, the twist may represent too small an effect to be a factor.

Comparison between the NLR results and imaging is extremely valuable. In addition to providing precise global geometry for the Rahe plane, the NLR data can provide precise topographic information regarding specific sites of interest identified in MSI images. The NLR and MSI teams wisely exploited this synergy, integrating detailed topographic information with imaging to help understand the character of various features on Eros (Cheng et al. 2001).



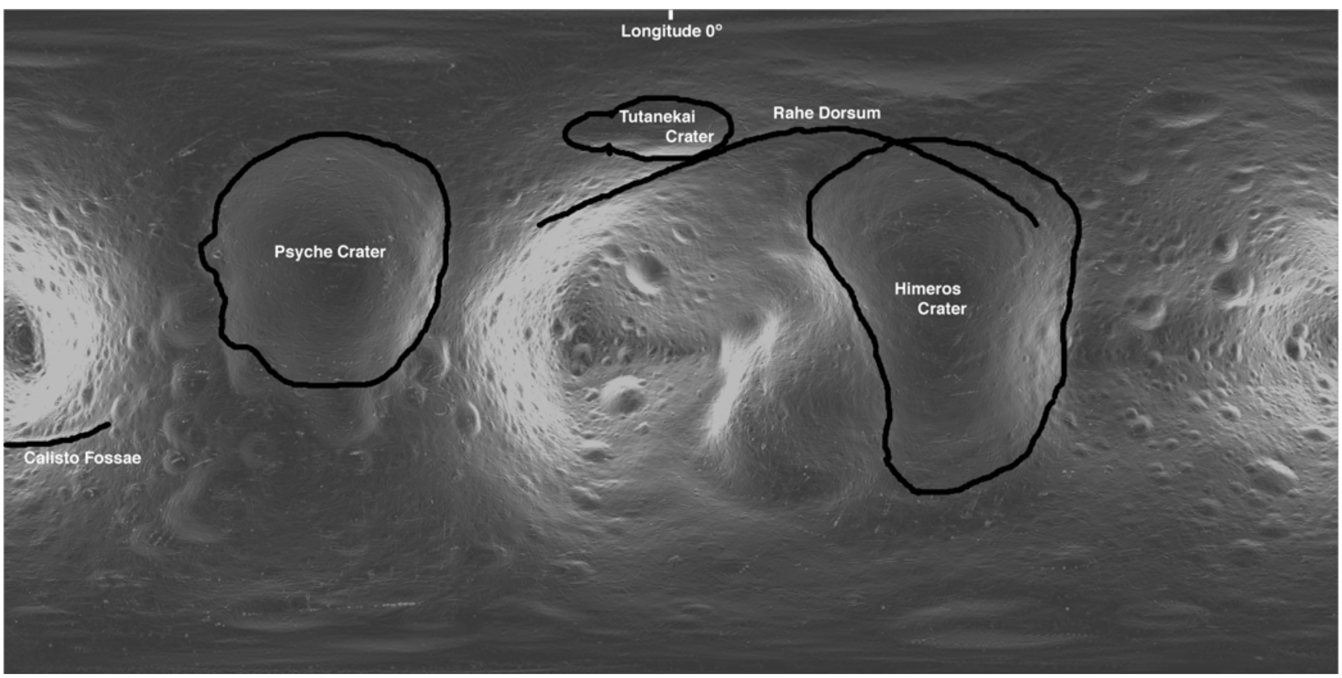


Fig. 9. a) NEAR Laser Rangefinder data on the shape and topography of Eros has been presented as a matrix of values representing the radial distance from the center of Eros as a function of latitude and longitude in 1/8 degree increments. Here that data set has been filtered to enhance edge effects and create a map of topographic features. Latitude runs vertically from –90° to +90° and longitude runs from 180°W to 180°E. The heel of the shoe (near longitude 25°W, cf. Fig. 7) is just west of the center; the toe is near longitude 180°, at the extreme left and right of this map, on the equator. b) Some key features labeled on the map (cf. Thomas et al. 2002).

Among the numerous detailed NLR profiles presented by Cheng et al. is one that crosses Rahe Dorsum just south of Tutanekai (Fig. 10). This location is just to the right of Tutanekai in Figs. 1 and 5, and just to the left of Tutanekai in Fig. 3. Cheng et al. noted that the ridge morphology in the vicinity of the NLR track across Rahe Dorsum (Fig. 10) had been interpreted from images "as consistent with compressional deformation (Veverka et al. 2000)," and added that "the NLR profile from a to f is also consistent with compression."

However, that portion of the profile is too limited in extent to test whether the topography is indicative of a fault displacement, let alone the unlikely connection with

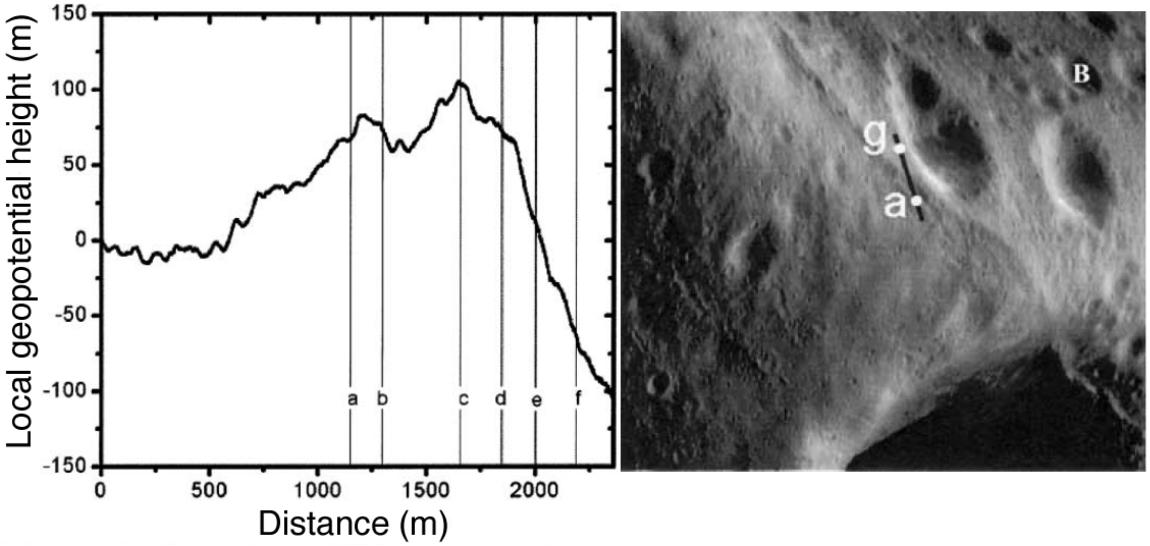


Fig. 10. A profile (left) based on NLR data across Rahe Dorsum, at a location (right) just west of the point of tangency to the rim of Tutanekai crater. The profile and image are from Cheng et al. (2002), but the units on the abscissa have been corrected). The locator view at the right is similar to the view in Fig. 3. This profile is oriented so that the vertical direction is parallel to the best estimate of the local gravitational field. Using this orientation and showing such a short profile, the scarp appears to drop down going from point *a* toward *g*, but in fact the scarp drops in the other direction (as in Fig. 5 and in other NRL data discussed in the Surface Profiles section).

compression. As discussed in the Thrust Fault Geometry section (especially Fig. 6), the trend of the terrain on both sides of a scarp must be considered in order to be useful as an indicator of thrust faulting or, more generally, of shear displacement along a dipped plane. The section shown by Cheng et al. (Fig. 10) does not include that neighboring terrain. It does show a steep cliff relative to the geopotential, but its relevance to the structural interpretation is not clear. In fact, the steep drop-off of the cliff in the NLR profile (relative to the gravitational potential) goes in exactly the opposite direction from the scarp in the images (e.g., Fig. 5). The scarp should drop from the concave side of Rahe Dorsum (the Tutanekai side) down to the convex side (Fig. 5) to be consistent with the images and the thrust fault model, the opposite sense from the cliff shown in Fig. 10. (Note too that the scale in the profile in Fig. 10 by Cheng et al. artificially steepens the appearance of the cliff.) Thus, although the profile shown by Cheng et al. is accurate, it is difficult to interpret without including the neighboring terrain.

In order to use the NLR data to understand the character of Rahe Dorsum and its relationship to the internal Rahe plane, we need to consider longer profiles and more of them. Fortunately NLR's precise, high-resolution global coverage provides an accessible and complete data set for constructing profiles across any portion of the surface of Eros. The next section describes a more complete set of profiles across the portion of Rahe Dorsum considered by Cheng et al., including an extension of the profile shown in Fig. 10. The profiles are then interpreted in the context of the relative position of the internal Rahe plane.

SURFACE PROFILES

The global shape defined by the NLR data set allows us to construct profiles across any selected line over the surface. Each profile represents the intersection of the surface with a plane (the "profile plane") defined by two radii from the nominal center, in the coordinate system used to generate Fig. 9. Because the shape data are presented as radii, and because Eros is a small, irregular body, construction of each profile must account for the fact that the directions of the radii change somewhat along even a short distance on the surface. Taking that geometry into account, conversion of the global data into profiles for selected sites is straightforward.

Consider a profile across the portion of Rahe Dorsum where the scarp-like appearance is most pronounced in the imaging, to the southeast of Tutanekai (Fig. 9b) where the ridge curves from Tutanekai towards Psyche. The location of this profile is indicated by line A in Fig. 11.

The profile itself is shown in Fig. 12a. The general rising trend toward the right follows the global shape of Eros, with the distance from the center increasing toward the end of the long axis. At its middle, the profile shown here crosses Rahe Dorsum, presenting the scarp-like geometry consistent with its appearance in images (e.g., Fig. 5).

Is the profile in Fig. 12 consistent with shear displacement on the Rahe plane? As discussed in the Thrust Fault Geometry section (Fig. 6), comparison of the slopes of the profile immediately on either side of the scarp is critical. These slopes are indicated by the straight line fits in Fig. 12b, and they are distinctly not parallel. The geometry is like that in

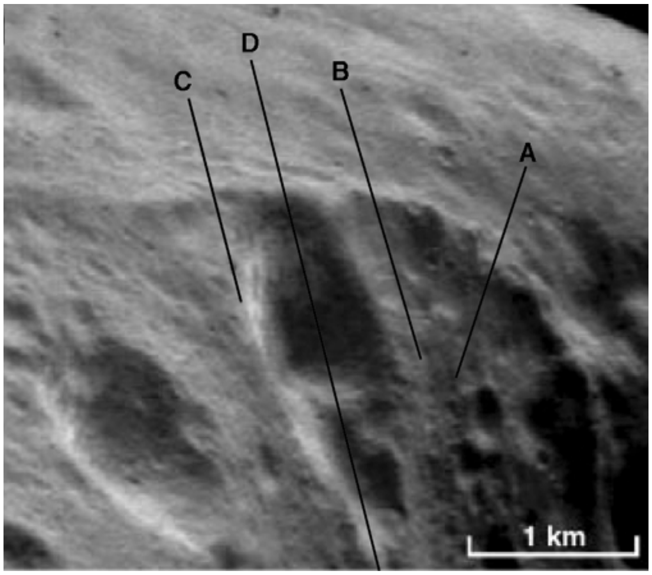


Fig. 11. A locator key for several topographic profiles (A–D) discussed in this section. Profile D runs through crater Tutanekai. The hooked portion of Rahe Dorsum runs to the right. This key is based on NEAR image 128933128. This same area appears (from various perspectives) in Figs. 1, 3, 4, 5, 7, 8, and 9.

Fig. 6d, not Fig. 6c. Hence this profile, while confirming the scarp-like character indicated by imaging, is not consistent with the thrust-faulting interpretation initially suggested by the NEAR team, nor (more generally) with any other form of shear displacement along the Rahe plane.

Also shown in Fig. 12b is the location of the internal Rahe plane, below the surface. More precisely, it is the intersection of the Rahe plane with the profile plane. The angle of this plane relative to the surface is very shallow. In fact, for the 500 m closest to the scarp, the Rahe plane is practically parallel to the surface and just below it. This geometry is also evident in Fig. 8e, which is very close to the view presented in Fig. 12. Consideration of Figs. 8e and 12 questions the hypothesis that Rahe represents a plane of weakness. It seems difficult to understand how the catastrophic impact that created the shape like that of Eros could have left a weak plane at this orientation. During that violent event, one would expect the mass at the toe end (upper right) to have moved closer to the mass at the heel end if the Rahe plane really was weak enough to allow displacement.

The relationship of the Rahe plane to the surface geometry in this profile is more suggestive of a plane of strength, rather than one of weakness. It is not consistent with the interpretation of a thrust-fault plane, where shear displacement has occurred. Instead, the Rahe plane seems to have defined the surface profile where it intersects the surface, as if its greater strength has resisted the processes that may have eroded away the neighboring terrain, just as strong strata or igneous intrusions can create ridges or scarps where they intersect the eroding surface of the Earth.

This interpretation is borne out by other topographic profiles across Rahe Dorsum. Next, consider a profile in Fig. 13, located along B in Fig. 11, which is close to the same location as the profile as that considered by Cheng et al. (Fig. 10 above). Here the profile represents the actual geometric profile and scales are the same in both directions, avoiding some of the complexity in interpreting the profile presented by Cheng et al. In Fig. 13, from right to left the profile runs in the sense from bottom to top in Fig. 11. This sense is consistent with the same direction of crossing Rahe Dorsum as in Fig. 12 (but opposite the sense as displayed by Cheng et al.).

In Fig. 13, as in Fig. 12 and even more clearly, we see that the trend of the terrain on either side of the scarp is not parallel and thus is not consistent with expectations for a thrust fault. Also, as in the previous profile, the position of subsurface Rahe plane (shown by the dark straight line) relative to the surface seems to suggest that its strength may define the surface topography. Where the surface is near the Rahe plane, it follows along the plane and around its edge, forming the ridge.

Another profile, which displays a similar character, is located at C in Fig.11 and shown in Fig. 14. As in the previous two cases, the slopes of the terrain on the opposite sides of Rahe Dorsum are not parallel, so this is not a compressional fault feature. Here the Rahe Dorsum is less scarp-like than the previous two cases, and more like a ridge. The geometry is consistent with the steep dip angle of the internal Rahe plane below, assuming that the ridge represents a strong plane intersecting the surface.

Next, consider the profile in Fig. 15, located at D in Fig. 11. This profile runs in the same sense as profile B, that is the right end of the profile is on the side of Rahe Dorsum opposite the side where Tutanekai crater is located. This profile crosses Rahe Dorsum where the ridge is tangent to Tutanekai crater, and it runs through both Tutanekai and through the smaller crater that overlaps Tutanekai, as shown in Fig. 11.

The profile shows that the shape of Tutanekai's interior is extremely asymmetrical, with one side sloping down along practically a straight line from where the crater wall osculates Rahe Dorsum down to the deepest part of the crater. Comparing this straight portion with the location of the Rahe plane suggests that the Rahe plane has controlled the shape of the interior of the crater. It appears that the Rahe plane has resisted excavation, again suggesting that it represents a surface of strength.

The profiles presented above cross a portion of Rahe Dorsum where the internal Rahe plane makes only a shallow dip angle with the surface. Indeed, the surface on one side of Rahe Dorsum in that area seems to follow one side of the Rahe plane. Next consider a site where the Rahe plane intersects the surface with a much larger dip angle: near the east end of Rahe Dorsum where it crosses within the giant crater Himeros.

A profile of the ridge at this location, constructed by Cheng et al. (2002) is shown in Fig. 16. Here, relative to the

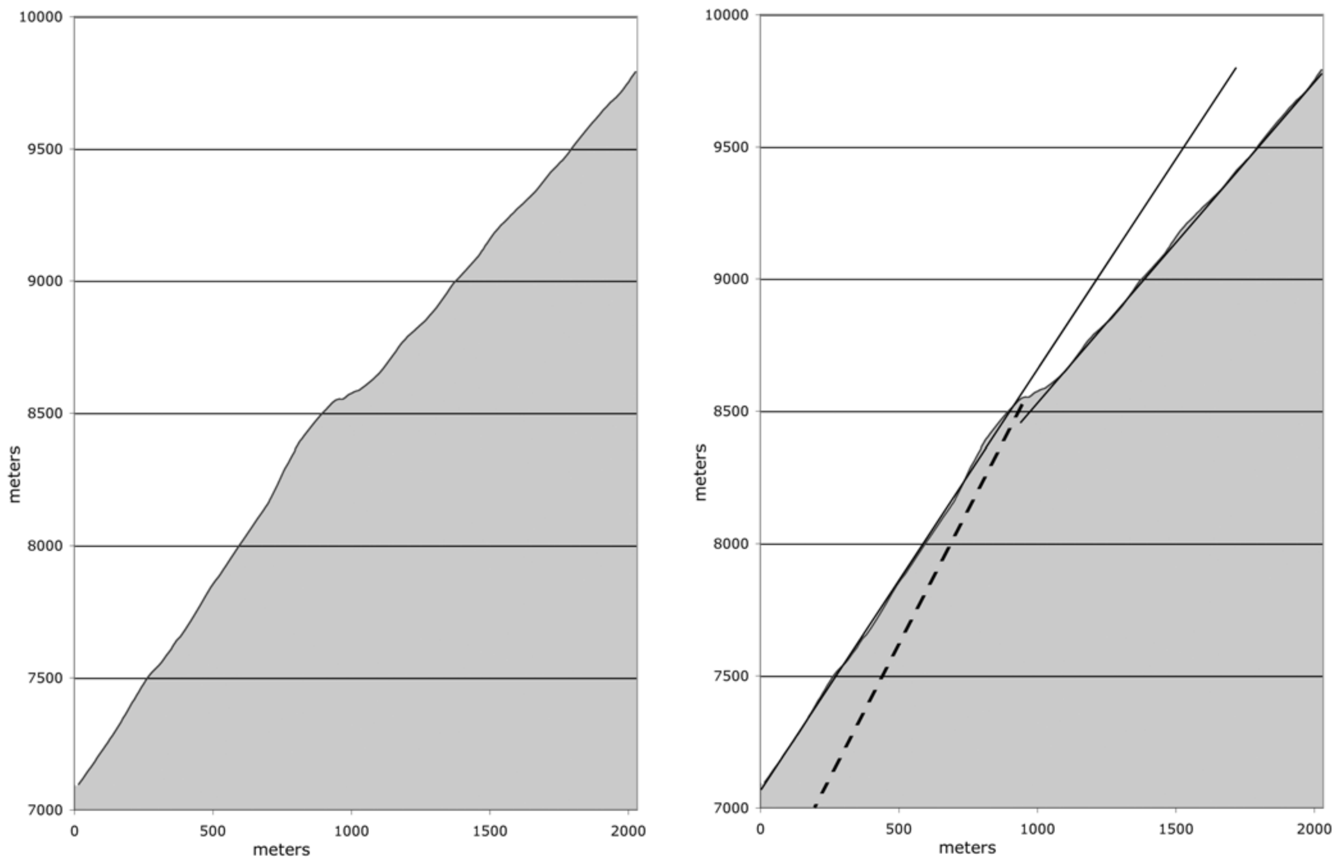


Fig. 12. a) A profile across Rahe Dorsum at location A (Fig. 11). The upper right direction is toward the top in Fig. 11. b) Lines fit to the profile on opposite sides of the scarp show that the geometry is more like Fig. 6d than 6c, so the geometry is not consistent with the proposed thrust faulting. The dashed line shows the position of the internal Rahe plane. The surface profile is consistent with the hypothesis that the plane strengthened the surface so that it resisted impact damage or erosion.

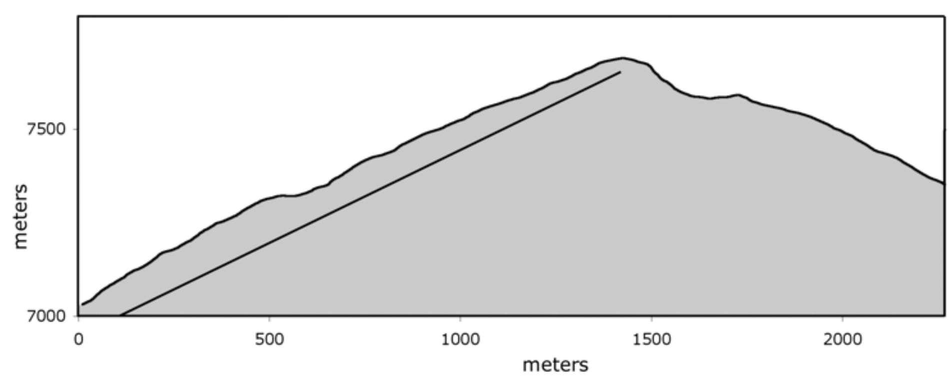


Fig. 13. A profile across Rahe at location B (Fig. 11), with the right side near the top in Fig. 11. This profile is very close to the location of the profile by Cheng et al. (Fig. 10), but the latter was plotted in the opposite direction, is tipped relative to this profile, covers a much shorter range, and used different scales that exaggerated the slopes. When those factors are taken into account, the profiles are in agreement. Note, however, that the steep drop-off to the right in Fig. 10 is actually a gradual slope at the top side of the scarp, while the actual drop off of the scarp (dropping to the right here) seemed to be the less steep slope (dropping to the left) in the display by Cheng et al. The solid straight line shows the position of the internal Rahe plane, the strength of which may define the flat surface just above it and shape and location of the scarp.

sloping inner wall of Himeros, Rahe Dorsum is a ridge rather than a scarp. Because of the shape of Himeros, one side of the Rahe ridge is quite steep (as shown in Fig. 16) relative to the direction of gravity. (Note that plots in early reports by the NLR team may have given the impression it was even steeper, before the abscissa was converted from spacecraft time to a distance scale). However, the steepness relative to the direction of gravity is not relevant to the issue of the structural meaning of the ridge. In fact, here the internal Rahe plane is nearly perpendicular to the surface, as shown in Fig. 16. This

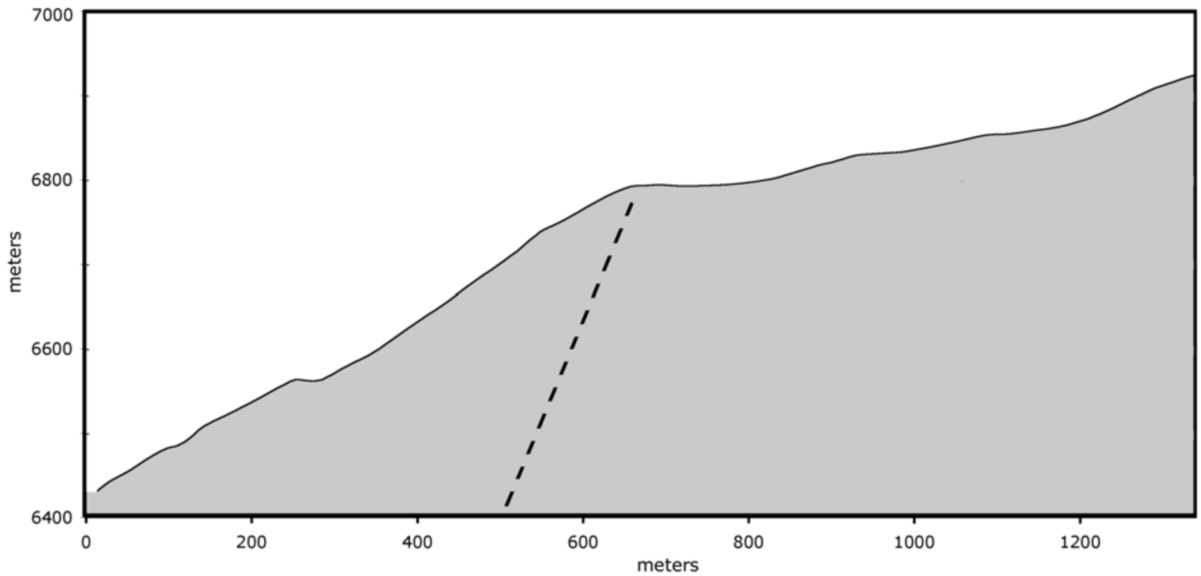


Fig. 14. Profile C (cf. Fig. 11) is at a location where Rahe Dorsum is more of a ridge than a scarp, which is consistent with the steep dip angle of the internal Rahe plane below, assuming that the ridge represents a strong plane intersecting the surface.

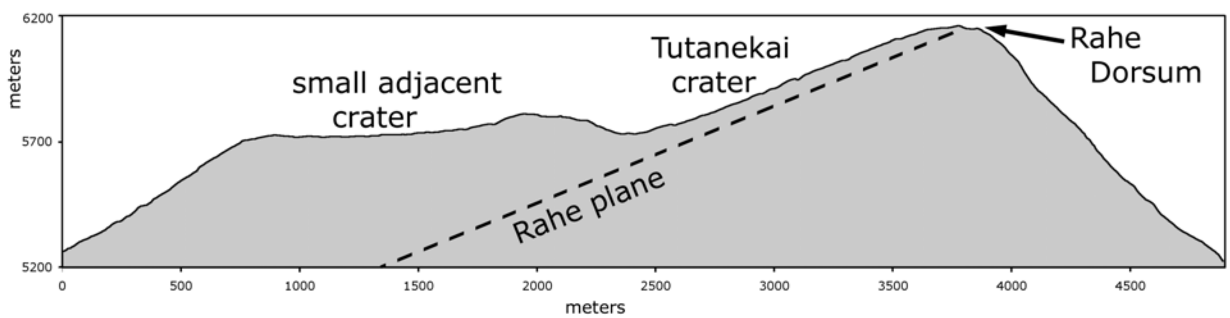


Fig. 15. Profile D (cf. Fig. 11) crosses Rahe Dorsum at the point where it is tangent to the rim of Tutanekai and it runs through Tutanekai and the smaller adjacent crater. Tutanekai crater appears to have penetrated to the Rahe plane, but not through it, suggesting that the strength of the plane resisted excavation and controlled the flat, inclined profile of the crater's interior.

geometry can be confirmed by inspection of Fig. 8a, where the view is along the Rahe plane and nearly perpendicular to the surface on the inner wall of Himeros.

The ridge geometry (as opposed to a scarp) is just what one would expect if the Rahe plane is a surface of strength. A plane of strong material intersecting the surface at such an angle and resisting erosion should result in a ridge. A terrestrial analog would be the Appalachian ridges, which represent the intersection of particularly strong (in that case stratigraphic) internal layers with the Earth's surface. In this interpretation, on Eros the strong material resisted the excavation of Himeros and survived as the ridge. The ridge thus represents the edge of the strong, interior plane.

IMPLICATIONS OF THE PLANE-OF-STRENGTH HYPOTHESIS

The topography of Eros around the intersection of the internal Rahe plane with the surface of the asteroid suggests that Rahe represents an internal surface of strength, rather than a fault plane. The interpretation that Rahe Dorsum's "morphology is consistent with a compressive fault plane" (Robinson et al. 2002) does not seem well supported: we have seen that the surface topography is not consistent with shear along a dipping plane, which is essential to a compressive fault; Eros lacks a lithosphere-like structure, which is an implicit element of the compressive faulting process; and no compressive driving force has been identified for the compressive thrust fault hypothesis.

Thus the statement that Rahe is "almost certainly a plane of weakness" (Robinson et al. 2002) is questionable. Of course, it remains possible that it is a plane of weakness, but it is hardly certain, and such a case has not been developed in the literature. In fact, the evidence presented above suggests that what defines the topography along Rahe Dorsum and at other intersections of the Rahe plane with Eros' surface is more likely a plane of strength.

The plane-of-strength hypothesis has implications for the

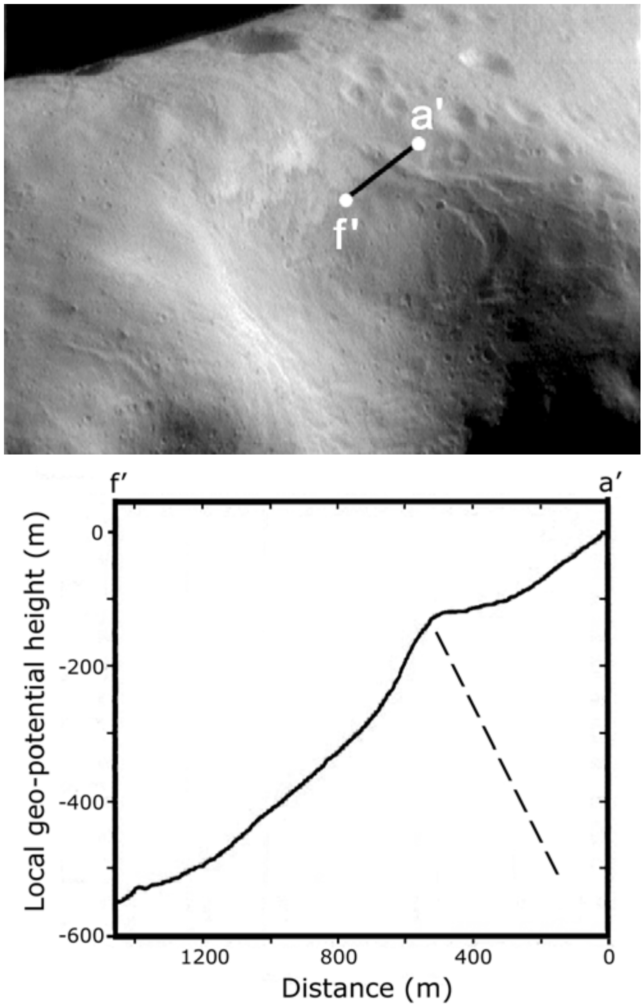


Fig.16. a) The location of a NEAR NLR profile within Himeros, and b) the profile (Cheng et al. 2002), with the position of the internal Rahe plane included. As in Fig. 14, when the plane is steeply angled down relative to the surface at the intersection point, a ridge is created, consistent with the strength of the plane having resisted impact damage and/or subsequent erosion.

history of Eros. For example, according to the compressive fault model, the fact that Rahe cross-cuts Himeros indicates "that it was created after Eros reached its current shape" (Robinson et al. 2002, see also Prockter et al. and Veverka et al.). However, the evidence that the Rahe plane is strong suggests just the opposite: in that case, the ridge within Himeros may be where the stronger material resisted excavation during formation of the crater. The implication is that Rahe predates the Himeros impact.

In fact, considering how such an internal surface of strength might have formed, it seems plausible that the Rahe plane predates Eros itself. As an S-type asteroid, Eros is probably composed of primitive ordinary chondritic material (Bell et al. 2002). Hence, the portion of the parent body from which Eros emerged was evidently modified little (if at all) by heating. But it is conceivable that other parts of the parent body were heated enough for partial melting. In that case, melt may have risen (or been forced through) a crack in the parent body. Then, upon solidifying, this igneous material formed a strong interior intrusion.

Subsequently, on disruption of the parent body, the fragment that we know as Eros could have included a portion of the igneous intrusion. This sequence of events could explain how a small asteroid of largely primitive material might include a strong igneous intrusion along an internal plane that passes through the entire body.

Such igneous intrusions on Earth, in the form of dikes or sills, are often stronger than the surrounding rock, resulting in ridges or flattened areas where the stronger rock preferentially resists erosion. On Eros, such an intrusion might similarly resist both sandblasting erosion by small impactors and excavation during formation of larger craters. Those processes might thus explain the topography that we observe where the Rahe plane meets the surface (Fig. 17). Where the plane intersects the surface at a large oblique angle, we find a ridge, e.g., within Himeros (Fig. 16) or at profile C (Figs. 11 and 14). Where the intersection is nearly parallel to the surface, we find a scarp (e.g., Fig. 12 and 13), and where the surface has been excavated down to the plane, the strong material defines a flat area, as within Tutanekai (Fig.15) or at the locations of profiles A and B (Figs. 11, 12, and 13).

A fully molten intrusion is just one end member of a range of metamorphic processes that might have occurred in a largely undifferentiated parent body to yield a plane of strength. More modest internal igneous metamorphism may have strengthened rock in a way that ultimately led to what we have seen on Eros. What processes are most plausible is a topic open to further consideration.

If the strong internal surface formed within the parent body (whether as an igneous intrusion or some other way), it is conceivable that it played a role in preventing Eros from fragmenting further and in structurally supporting Eros' irregular shape. More generally, given that one of the few asteroids viewed close up shows these signs of an internal plane of strength, similar intrusions might be involved in supporting the shapes of other irregular asteroids as well.

If the plane of strength developed by igneous intrusion or thermal modification, it likely would have a composition somewhat distinct from that of the undifferentiated material believed to compose the bulk of Eros. In principal, such differences could be detected by remote sensing of reflectance characteristics. However, only a narrow band of the stronger material would intersect Eros' surface, so high resolution sensing would be required for a definitive study. It is possible that some of the material has been spread by impacts and transported by down-slope motion, but it would then be diluted and/or displaced so as to difficult to recognize or to identify with the Rahe plane. The problem is compounded by uncertainty about what type of material to expect in a plane of strength. If it is an intrusion from a partial melt, the composition could depend strongly on the particular conditions of its formation.

Nevertheless, there is some remote-sensing reflectance information available. Here I speculate on what it might mean in regard to the partial-melt explanation for the plane of strength, in order to stimulate further discussion and serve as a template for linking the evidence and models. Albedo variations are generally minimal, but the surface is distinctly brighter on the interior rim walls of Himeros, Psyche, and Tutanekai, all of which are locations where large impacts exposed portions of the Rahe plane (Fig. 18). These locations display color and reflectance properties similar to one another (Murchie et al. 2002). The bright portion of the interior of Tutanekai correlates perfectly with the area where the shape appears to be controlled by the strength of the Rahe plane (cf. Fig. 11 which distinctly shows the bright area, and Fig. 15 which shows the relative position of the Rahe plane). The correlation is not as strong elsewhere, however, and, in all the craters, exposed material has likely been smeared around to some degree by the initial impact and subsequent mass-wasting.

At near-infrared wavelengths Eros appears quite uniform, but reflectance spectra from the bright areas in Himeros and Psyche are similar to one another and somewhat different from the more typical surface of Eros (Bell et al. 2002). The bright portion within Tutanekai may also have a similar near-infrared spectrum to the other bright areas (Izenberg et al. 2003). The difference between the spectra of these brighter areas and the more typical surface may be a result of "space weathering" or compositional differences or both (Bell et al. 2002). Space weathering is often invoked to explain why surfaces exposed to space "darken, redden, and lose spectral contrast" (Bell et al. 2002). It is possible that the brighter surfaces inside Himeros, Psyche, and Tutanekai represent material that has been relatively freshly exposed by landslides, whereas the rest of the surface of the asteroid has had more exposure time during which it was "weathered."

However, the spectral difference might alternatively represent a difference in material composition. The spectrum in the bright areas could be indicative of a proportion of olivine relative to orthopyroxene somewhat less than the average surface composition (Bell et al. 2002). Such a paucity of olivine might be consistent with the idea that the Rahe plane represents an igneous intrusion of melted material through a crack in otherwise primitive chondritic rock. If some part of the parent body, presumably deeper in the interior, were heated enough to melt partially, the liquid would be relatively depleted in olivine (McCoy et al. 2006). Moreover, such an olivine-depleted magma would be less dense, which might have played a role in moving the material up through cracks in a cooler outer layer.

Even if the strengthening did not involve a molten intrusion, any metamorphic process that created the plane of strength would have affected the petrology of the materials involved. It may be worth exploring further whether such processes might have produced spectral signatures consistent with observations, perhaps as alternatives to earlier interpretations.

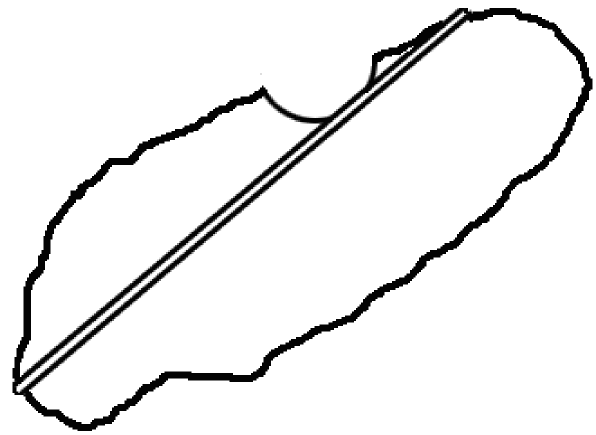


Fig. 17. A schematic sketch summarizes how a strong internal surface (here shown by the parallel straight lines), such as an igneous intrusion, may influence the shape of the surface. Where it intersects close to normal to the surface (lower left in this sketch; inside Himeros on Eros) it creates a ridge. Where it intersects at a shallow angle (upper right in this sketch; between Tutanekai and Psyche on Eros), it may create a scarp, with the surface closely following the plane of strength on one side. Where a crater reaches the plane of strength (top center of sketch; e.g., Tutanekai on Eros) the interior shape of the crater may be affected and the material of the intrusion may be exposed.

Such processes did not happen in the current body we know as Eros, because the Rahe plane runs entirely through the body, leaving no room for a magma source location. Moreover, Eros is probably too small to have undergone enough heating. Instead, the plane of strength was probably formed while Eros was still part of a much larger parent body. Then, subsequent to intrusion of the olivine-depleted magma that formed the Rahe plane, the parent body broke up, creating the fragment we know as Eros. During that event, the internal plane of strength represented by the solidified intrusion may have played a role in holding Eros together. Then during subsequent collisions suffered by Eros, the plane may have helped resist catastrophic break up. The Rahe plane would also resist collisional erosion along its intersections with the surface, explaining the ridge and scarp morphologies seen at those locations (as in Fig. 17).

SUMMARY AND CONCLUSION

The identification of a ridge system on Eros that appears to represent the intersection of an internal structural plane with the irregularly shaped surface was a major discovery of the NEAR mission. The scarp-like form of a portion of Rahe Dorsum initially may have seemed reminiscent of terrestrial thrust faults. Early reports from the NEAR team thus suggested that compression was involved and that the internal plane was a fault, i.e., a plane of weakness along which displacement had occurred.

As described above, a reconsideration of the geometry of this plane suggests that it is a plane of strength rather than weakness. Several pieces of evidence point toward this conclusion:

1. The association of a scarp with horizontal compression is based on experience with terrestrial planets, where fault planes dip obliquely down relative to the surface through a lithosphere. That connection would not be relevant to a fault plane that runs entirely through an irregularly shaped body.
2. In principle, a scarp could be created by shear displacement along the Rahe plane (other than a thrust fault), but the observed profiles are not consistent with that model, because of the mismatch in slope on opposite sides of the scarp.
3. The placement of the Rahe plane obliquely lengthwise along the body of Eros would be difficult to reconcile with its being a plane of weakness. Rather it suggests that this plane might be a reinforcing feature, helping to support the irregular elongated shape.
4. The topography at the intersection of the Rahe plane with the surface is consistent with its being a plane of strength that has resisted the effects of collisions. Where the plane reaches the surface with a low dip angle, a scarp is found at the edge of the plane. Where the intersection is more nearly perpendicular, the plane stands up as a ridge.
5. Crater Tutanekai penetrated to the Rahe plane, but not through it. The topography in the crater's interior is flattened where it meets the plane, consistent with the strength of the plane having resisted penetration.
6. Exposure of the Rahe plane in several craters hints at a different albedo and reflectance spectrum than typical for the surface, suggesting a difference in composition, which would not be expected if the plane were a fault. A difference in composition, if real, could explain why the plane is stronger.
7. Given Eros' predominantly chondritic composition, the parent body was at most partially melted, and that only in some places. Igneous intrusion through a crack in the primitive material could have produced a vein of stronger rock than the surrounding, more weakly consolidated chondritic rock. The Rahe plane might have formed in this way. A relative depletion of olivine in this material, if confirmed, might have occurred in a partial melt elsewhere in Eros' parent body.
8. Similar to igneous dikes and sills on Earth, such a strong internal structure would resist erosion where it meets the surface. The surface morphology on Eros may be controlled by the plane of strength in a way similar to the ridges and platforms that dikes and sills form at the surface of the Earth. On Eros, the idea that Rahe represents an internal plane of strength is thus consistent with both the surface morphology and with hints of a compositionally different material from the rest of Eros.

It is plausible that such a vein of reinforcing material could have helped what we know as Eros to have survived the destruction of its parent body. Irregularly shaped and elongated bodies are fairly common among asteroids. If Eros is typical, perhaps similar reinforcement by internal veins of strong material plays a role in the support and survival of some of those other bodies as well as Eros.

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