CARTOGRAPHIC AND TOPOGRAPHIC MAPPING OF THE ICY SATELLITES OF THE OUTER SOLAR SYSTEM

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ABSTRACT:

Cartographic and topographic mapping of the major satellites of the Outer Solar System has been in progress since the late 1980's, beginning with Voyager image data, and incorporating Galileo and recently Cassini imaging data as released to the public. Global image mosaics, based on cartographic control nets, have been produced for all these satellites. In addition, digital topographic maps have been produced for restricted areas on the Galilean, Uranian satellites, and Triton. Global topographic maps as well as limited high resolution topographic samples have been produced for the Saturnian satellites. These data have been used to investigate the properties of the icy outer layers (esp. Europa and Io), discrimination between competing hypotheses of geologic origins (on Triton, Ganymede, Europa, and Enceladus for example), and in some cases the thermal histories of these bodies (esp. Ganymede and Dione). These data are available on request for use in mapping and modelling of geologic and geophysical processes.

1. INTRODUCTION

1.1 Purpose

Since 1979, Voyager, Galileo, and now Cassini have unveiled over a dozen new worlds in the outer Solar System. With the exception of Io (its soulful dioxide coatings notwithstanding) these moons of the outer planets are almost all dominated by icy mantles tens to hundreds of kilometres thick. Although subject to similar geologic forces as on Earth or the Moon, their icy composition leads to geologic landforms that are both familiar and alien. Key to understanding these landforms and the geologic processes and stresses responsible for them are accurate cartographic and topographic tools and data sets. Several groups have been working these problems, and here I report on mapping products for these objects generated by our group at the Lunar and Planetary Institute over the past decade.

1.1.1 Cartographic Mapping: Production of reliable global maps is key to testing models for tectonic feature formation and global heating. Using USGS ISIS software, global maps of nearly every major satellite (those larger than ~100 km radius) have been produced. Control of images to produce global mosaics has been an ongoing task but is critical to mapping reliability. Starting with satellite radii from Thomas et al., (2007) and other sources, we have produced independent control networks for all icy satellites. Mapping of Saturnian satellites is ongoing as new data are released to the PDS, but other satellite mapping has been completed.

1.1.2 Topographic Mapping: Two topographic techniques are applied, either separately or in combination. Stereogrammetry has been the workhorse for these bodies, especially in the absence of altimetry instruments. Stereogrammetry provides reliable height information at all wavelengths but its dependent on scene content. Large areas of smooth nearly featureless volcanic plains on Io are not mappable using this technique, for example. Most icy satellites have high surface contrast at small wavelengths and stereo matching provides excellent results. However, stereo coverage can be poor in many areas, especially at Jupiter, and the stereo matcher degrades digital elevation model (DEM) resolution relative to the original images by factors of 5 or more. Shape-from-shading (photoclinometry, PC) has greatly expanded areal coverage of topographic mapping and produces DEMs with high resolution identical to the original images, but is not as stable at wavelengths longer than 50-100 pixels in the image plane. In many instances, however, stereo and PC overlap, allowing the former to control the uncertainties of the later. This merged stereo-PC technique has been especially profitable for Europa and the Saturnian satellites.

2. JOVIAN.GALILEAN/MEDICIAN SATELLITES

2.1 Cartography

Unlike the new systematic Cassini global mapping mosaics for the icy satellites of Saturn, Galileo's crippled communications has a near-catastrophic impact on cartography including both global and especially topographic mapping. Global mapping of the Galilean satellites is possible at 1-kilometer scales (not 200 meters as should have been), and these maps are now complete (Figure 1), based on our independent cartographic network. Mapping at 200-300 meters was also acquired by Galileo, but only for 5 to 20% of these surfaces. These maps combine the restricted Galileo and more global (but lower resolution) Voyager mosaics, and include near-global coverage in 3 colours.

In addition, *all* Galileo high-resolution (5 to 500 m/pixel) images of the 4 satellites have now been coregistered to the global control network (e.g., Figure 2), integrating them into our global digital map bases. This work (as on all the satellites) has been critical for accurate topographic mapping and DEM production. All of these products will be published together in 2008.

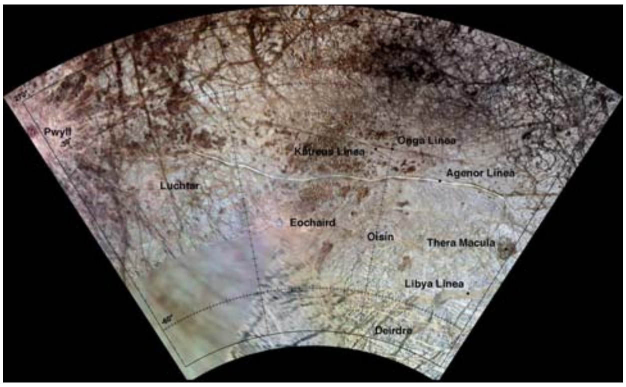

Figure 1. Quadrangle Je13 from global mosaic of Europa at 1 km resolution. Map is in Lambert equal area projection.

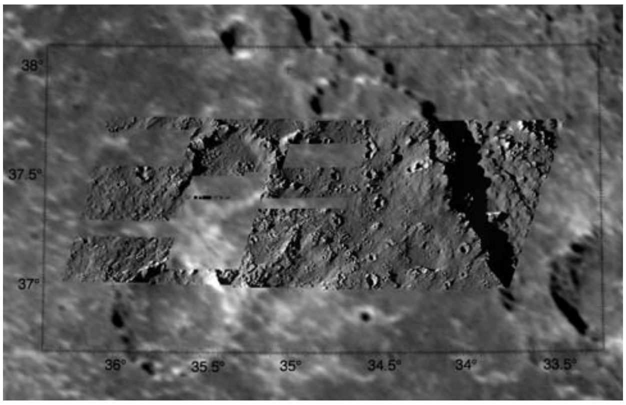

Figure 2. Controlled mosaic of an arcuate scarp in the concentric multiring Valhalla impact basin, Callisto. High-resolution mosaic (at 55 m/pixel, and including downlink gaps) has been overlain on low-resolution global mosaic for context.

2.2 Topography

Topographic data of the Galilean satellites is sparse but critical for understanding their geologic evolution. Topographic mapping is now essentially complete for all possible stereo and PC sites. Almost all topographic mapping sites are restricted to 1 to-4 image mosaics of small discontinuous areas of the surfaces, providing 10 and 70% global topographic coverage (with best at Io and poorest for Callisto and Ganymede). Stereo mapping parameters are completely nonsystematic from site to site. Many stereo sites were acquired at relatively high solar illumination, precluding use of coincident photoclinometry. Europa (Figure 3) is the happy exception to this rule.

2.3 Geology and Geophysics

On Ganymede, viscous relaxation of impact craters and furrows dominates ancient cratered terrains. Mapping of these craters indicates that relaxation and the higher heat flow responsible for it ceased (or declined) at or shortly after the time of bright terrain formation. Ancient impact features larger than 100 km are also radically different from similar sized recently formed impact basins, showing a clear evolution with age (Schenk 1993; Schenk, 2002; Schenk et al., 2004b). This variability reveals the effects of decreasing heat flow with time. Topography has also shown that smooth lanes of bright terrain are topographically depressed, consistent with emplacement by lower-viscosity water lavas (Schenk e al., 2001a). On Callisto, landform degradation dominates (Figure 2), creating “smooth” areas of dark material. The uniform albedo of these deposits allows us to use PC techniques. These units are not entirely “smooth,” but are heavily cratered and in some areas feature undulating topography and linear ridges that could be compressional in origin.

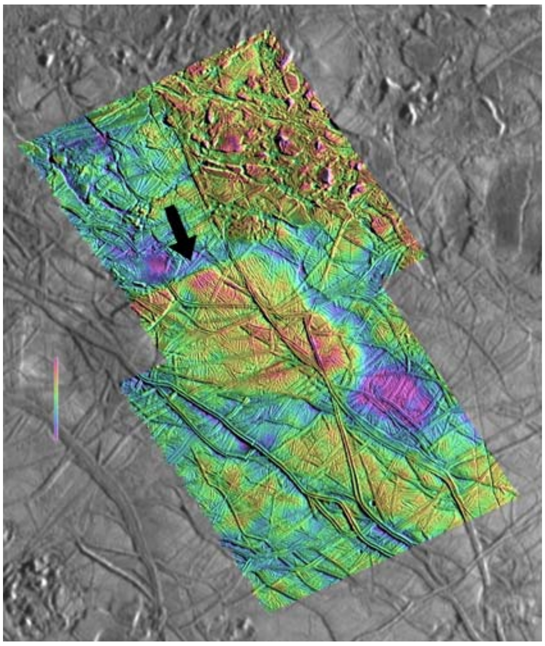

Figure 3. Controlled DEM of fault-bounded plateau on Europa. High-resolution mosaic (44 m/pixel) has been colour-coded to show topography (reds high, blues low). Relief across fault scarp (arrow) is ~400 m (Nimmo and Schenk, 2006). Topographic range shown is ~750 m. Data from stereo-photoclinometry combined.

Discoveries on Io include a 40-m deep lavas channel (Schenk and Williams, 2004), one of the largest landslides in the Solar System (Schenk and Bulmer, 1998) as well as measurements of smaller scale mass wasting deposits (Moore et al., 2001), and global topographic surveys of shield volcanoes (Schenk et al., 2004a) and mountain distributions and elevations (Schenk et al., 2001b; Williams et al., 2004).

On Europa, additional DEM work has discovered the wavy topography of chaos (as evidence supporting the diapiric model: Schenk and Pappalardo, 2004), a 250-m-deep dark depression of unusual composition (Prockter and Schenk, 2005), and the thickness of the ice shell based on changes in impact crater morphology (Schenk, 2002). Topographic mapping has also been important in characterising surface slopes on Europa as constraints on landing craft and radar instrument designs (Schenk, 2005).

Among the highlights on Europa is the unexpectedly high range of relief. Often quoted as having relief of only a few hundred meters, several sites have been found where relief exceeds 800 meters (e.g., Prockter and Schenk, 2005; Schenk et al., 2008), both above and below the local mean. In addition, regional scale variations are pronounced. Some regions of Europa are divided into topographic provinces, dominated by either flat or undulating ridged plains, plains pocked by numerous depressions, or by rugged disrupted terrains. Normal faults 350-400 meters high have been identified (Figure 3: Nimmo and Schenk, 2006). The persistence of these high amplitude topographic features all point to an ice shell that is not thin or weak, but that can support topography.

3. MID-SIZED SATURNIAN SATELLITE

3.1 Cartography and Topography

Cassini imaging as of October 2007 allows for global cartographic control and mapping (Figure 4) on the middle-sized icy satellites of Saturn down to resolutions of 400-500 m (over >75% of their surfaces). These include Phoebe, Iapetus, Rhea, Dione, Tethys, Enceladus, and Mimas. Global topographic maps have also been completed for Rhea and Dione and large parts of the other satellites at resolutions of 0.5 to 1 kilometre (Figure 5). In addition, isolated high resolution DEMs have been produced from Cassini data on many of the satellites (Figure 6).

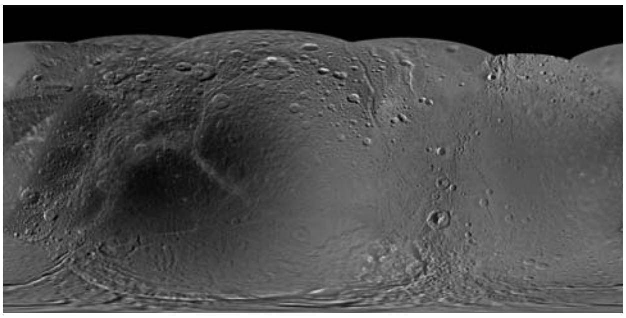

Figure 4. Global map of Dione (as of April 2008). Base resolution of global product is 400 m.

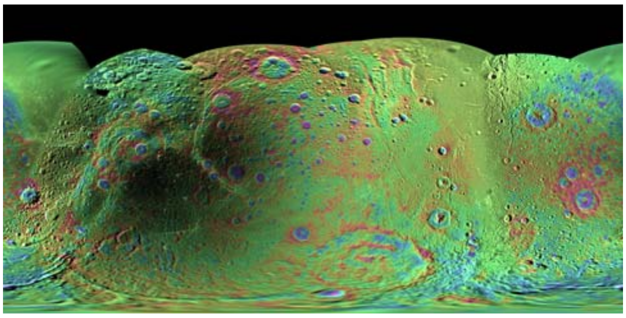

Figure 5. Global topographic map of Dione (as of April 2008). Global base map (Figure 4) has been colour-coded to show topography (red high, blue low). Total dynamic range is ~5 km. Topographic data are from stereogrammetry and photoclinometry.

3.2 Geology and Geophysics

Most of the icy Saturnian satellites are heavily cratered and impact effects dominate topography. Large degraded basins 350-500 kilometres across (and not apparent in imaging) are revealed on Rhea and Dione. Topography also reveals radial gouges centred on several of these ancient impacts (Figure 5), as well as two crossing orthogonal sets of grooves or ridges on Rhea, indicating that this satellite was more active than the cratered surface might suggest. On Tethys, we see the topographic signature of smooth plains, despite the fact these plains are heavily cratered. Topography also suggests the presence of a circumferential ridge 350-400 km beyond the rim of the Odysseus impact basin, indicating that this impact may have globally modified the shape of Tethys.

A major result of the Cassini topographic data is the extent of viscous relaxation on these satellites. Several large ancient basins on Tethys and Rhea are partially relaxed (Moore et al., 2004; Schenk, 2006), but not some younger basins, such as Odysseus on Tethys (Moore et al., 2004). A surprise was the abundance of relaxed smaller craters (D~10-30 km) on Dione (Figure 7) discovered from Cassini in association with smooth plains, indicating that heat flow was significantly higher in the past. Modelling indicates that residual impact heat beneath the crater floor is also required to explain the anomalously high central peaks seen on Dione (Dombard et al., 2008), some of which rise 3 to 5 kilometres above the surrounding plains (Moore et al., 2004; Schenk, 2006)! Larger craters on Dione are highly relaxed, including Evander (Figure 6; Schenk, 2006). Extensive relaxation of craters also occurs on Enceladus and mapping and modelling is in progress (Schenk, 2006).

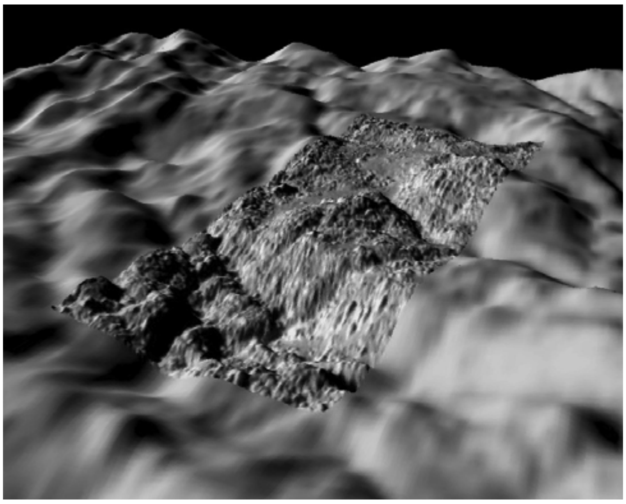

Figure 7. Perspective view of the south polar terrains on Enceladus. Colour-coded DEM is based on photoclinometric analysis of the highest resolution (~10 m/pixel) image currently available of the surface.

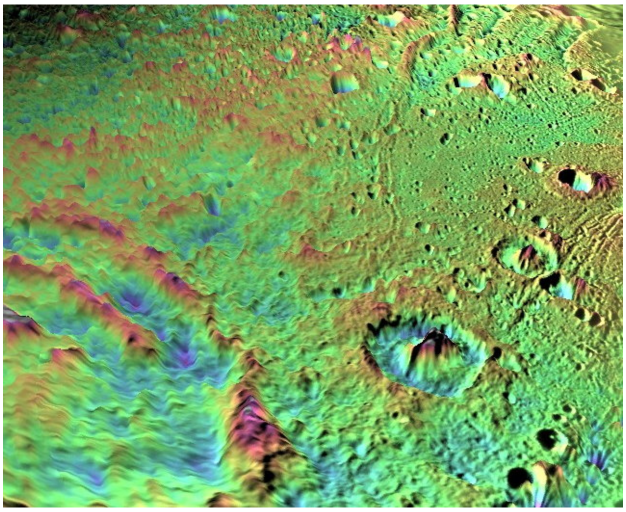

Figure 6. Perspective view of relaxed central peak craters (lower right) on Dione. Data from Figure 5. Central peaks are 3 to 6 km high and project well above the ground plane. At bottom left are the concentric inner ring and rim scarp of the relaxed Evander impact basin (D~350 km). Vertical exaggeration is considerable.

On a global scale, we confirm the depressed topography of the south polar terrains, but have also discovered large scale "dimples" in the topography of Enceladus (Schenk and McKinnon, 2008). These include at least two broad depressions roughly 100 km across and 1 to 1.5 km deep. These are located near the equator and at roughly 40°N latitude. They are located within older cratered terrains or on the contact between cratered plains and very young ridged plains, indicating that there is no correlation with geology. They could represent isostatic warping of the surface over irregularities in the rocky core or over downwelling/upwelling plumes in the icy mantle, or more likely isostatic depressions over mass anomalies.

4. URANIAN & NEPTUNIAN SATELLITE

4.2 Uranian Satellites

Voyager 2 data from 1986, obtained during southern summer, provided views of only 25-45% of the surface, almost all at southern latitudes (Figure 7). Excellent stereo imaging was obtained for Miranda and Ariel (Figure 8) and good stereo for parts of Titania. These data are locally supplemented by terminator photoclinometry. Oberon, Umbriel and Puck were too far away for anything other than reconnaissance images. DEMs of these satellites are largely unpublished but early analyses documented the depths of craters on the three mapped satellites (Schenk, 1991), and showed that some large craters on Ariel are also viscously relaxed or flooded by lavas (Schenk and McKinnon, 1998).

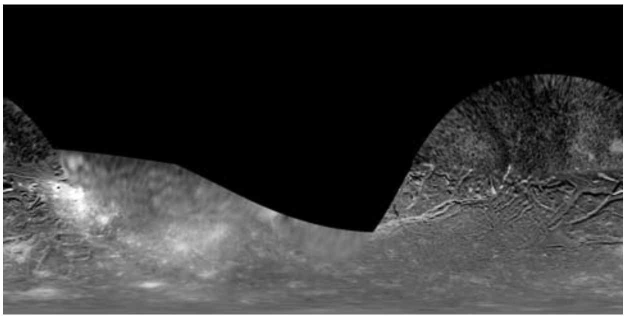

Figure 7. Global map of Ariel. Map is in simple cylindrical projection. Note northern hemisphere obscured by darkness, and use of Uranus-shine images north of the equator. Dark swath extending northward may be extension of volcanic plains.

4.3 Triton

Geologically useful stereo DEMs of Triton based on Voyager images cover only a modest fraction of the surface (<10%). Although these data have poor resolving power (50-200 m vertical), they were sufficient to demonstrate that the centres of cantaloupe terrain ovoids are depressed a few hundred meters (Schenk and Jackson, 1993). The poor performance of these data products is due mainly to the small stereo angles (imposed by the encounter geometry and distance), and by the inherently low topography of the surface. Few features on the surface have amplitudes greater than 250 m. Instead we rely on photoclinometry, which covers a 10-15° swath parallel to the Voyager terminator (Figure 9). These data have resolutions of 0.7 to 1.5 km and much higher vertical fidelity than stereo products.

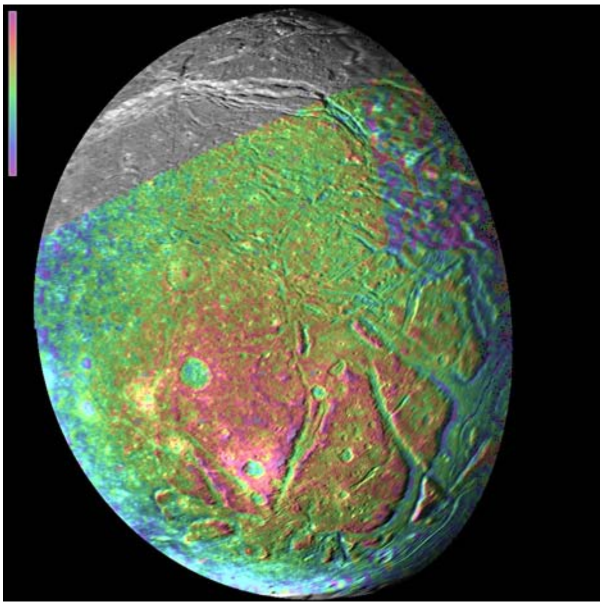

Figure 8. Topographic map of Ariel. Orthographic projection of base map has been colour-coded to show topography (red high, blue low). Topographic range displayed in colour bar is ~5 kilometres.

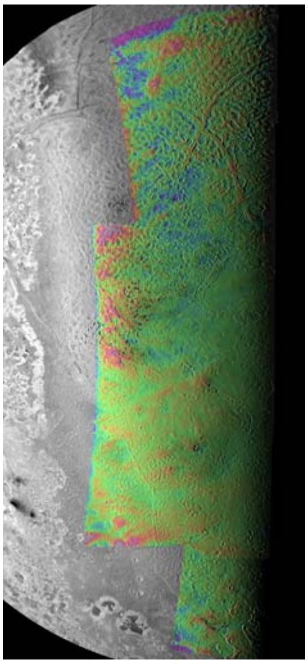

Figure 9. Topographic map of equatorial regions of Triton. Orthographic mosiac (north to right) has been colour-coded to show topography (red high, blue low). Total dynamic range is ~0.5 km. Data derived form photoclinometry only. Individual geologic features are well represented, but long-wavelength topography (likely of very low amplitude) is not regarded as reliable. Large amplitude features along the left edge of the DEM may be photoclinometric artefacts.

5. CONCLUSIONS

Cartographic and topographic mapping of the icy satellites of the Outer Solar System is an ongoing task, especially for the

Saturnian system. These data provide information otherwise unattainable regarding the properties of the icy outer layers (esp. Europa and Io), discrimination between competing hypotheses of geologic origins (on Triton, Ganymede, Europa, and Enceladus for example), and in some cases the thermal histories of these bodies (esp. Ganymede and Dione). The morphology and topography of impact craters, volcanoes, faults, and other geologic features and province serve as probes into the interiors of these bodies. These data are available on request for use in mapping and modelling of geologic and geophysical processes.

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