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WORMS OF GANYMEDES - HAZARDS OF IMAGE "RESTORATION"

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All image systems have limits to their resolution: a point source gives rise to a small blur spot. The effect is that images are smoothed: components with higher spatial frequencies are attenuated. Indeed, above some frequency signals are completely lost; in a good optical system this corresponds to the diffraction limit, in a poor one the limit will be lower. One can attempt to "restore" image components below this limit by amplifying some frequencies, undoing the attenuation introduced by the imaging system.

Unfortunately, all image brightness measurements are also corrupted by noise. Noise is amplified with the signal when the "restoring" procedure is applied. Typically the noise in brightness measurements made at different points is independent; the spatial spectrum of noise is flat. After the filtering operation however one finds a non-uniform spectrum. Low frequencies are passed through, higher frequencies are amplified; frequencies near and above the absolute resolution limit of the imaging system are attenuated.

Noise in the "restored" picture thus is (roughly) band-pass; it is spatially coherent. What does band-pass noise look like? Band-pass noise tends to have bumps and wrinkles of a size commensurate with waves at the spatial frequencies which have been amplified most. Images of band-pass noise have a dimpled, mottled, convoluted, "wormy" character, a little like the cortex of the brain or close-up pictures of orange peel.

Such effects can be seen also in tomographic reconstructions, where convolutional filters accentuate higher frequencies in noisy measurements of beam absorption (1). This is unavoidable since the projection process in effect attenuates these higher frequencies; the reconstruction algorithm then must undo this selective filtering by a process vaguely similar to differentiation; actually Hilbert transformation.

Recently researchers have become more aware of the "unstable" or "ill-conditioned" nature of the image restoration problem (2). It is acknowledged that severe "error propagation" can occur.

Band-pass noise effects are most noticable when the image is oversampled, that is, has been specified on a grid of points spaced more closely than the basic resolution of the imaging system. If image sampling matches the resolution, the coherence of noise is less noticable, and the appearance is more like that of independent noise with which everyone is familiar.

Images containing band-pass noise can be misinterpreted. A number of "features" seen in restored pictures of Ganymede taken by Pioneer 10 (3), for example, are mere undulations in the band-pass noise resulting from the "restoring" process. In particular, three round details, seen in figure 5 of that paper, claimed to be maria, fall in this category. These "features" do not match any of the surface markings apparent in pictures of Ganymede taken by Voyager 1 and 2 (4-7). The area concerned lies in a large dark cap-like region and does not differ substantially from other parts of the same region. The results of such image alterations must obviously be interpreted with care.

In fact, image enhancement infrequently shows features which are not visible in a well prepared transparency of the original image. Spatial frequencies above the cutoff of the imaging system cannot be restored in any case; lower frequency signals stand in the same ratio to noise before and after "enhancement".

At times the dynamic range of the image is reduced by removing low frequency components. Conversely the contrast of higher frequency components can be increased given the same dynamic range. This, in a sense, is overdoing the "restoration" process; or perhaps applying it to an image which was not degraded in the first place.

Reducing low frequency components has serious side effects since it reduces the shading apparent on smoothly curved surfaces. We use this important depth-cue to recover the shape of objects (8). When we cannot recover the shape, it becomes difficult to assign significance to the brightness patterns we do perceive. Are they the result of spatial variations in the reflective properties of the surface or are they the result of differences in surface orientation? Conversely one may see a bump in brightness distribution due to band-pass noise as a "crater".

Image processing methods allow one to fit the information of interest into the very limited dynamic range of the printed page. The spatial resolution and density resolution of a half-tone print is very much worse than that of a piece of film. The image can be processed to bring the features of interest into the useable reproduction range of available printing methods. This is where the real utility of image processing methods lies.

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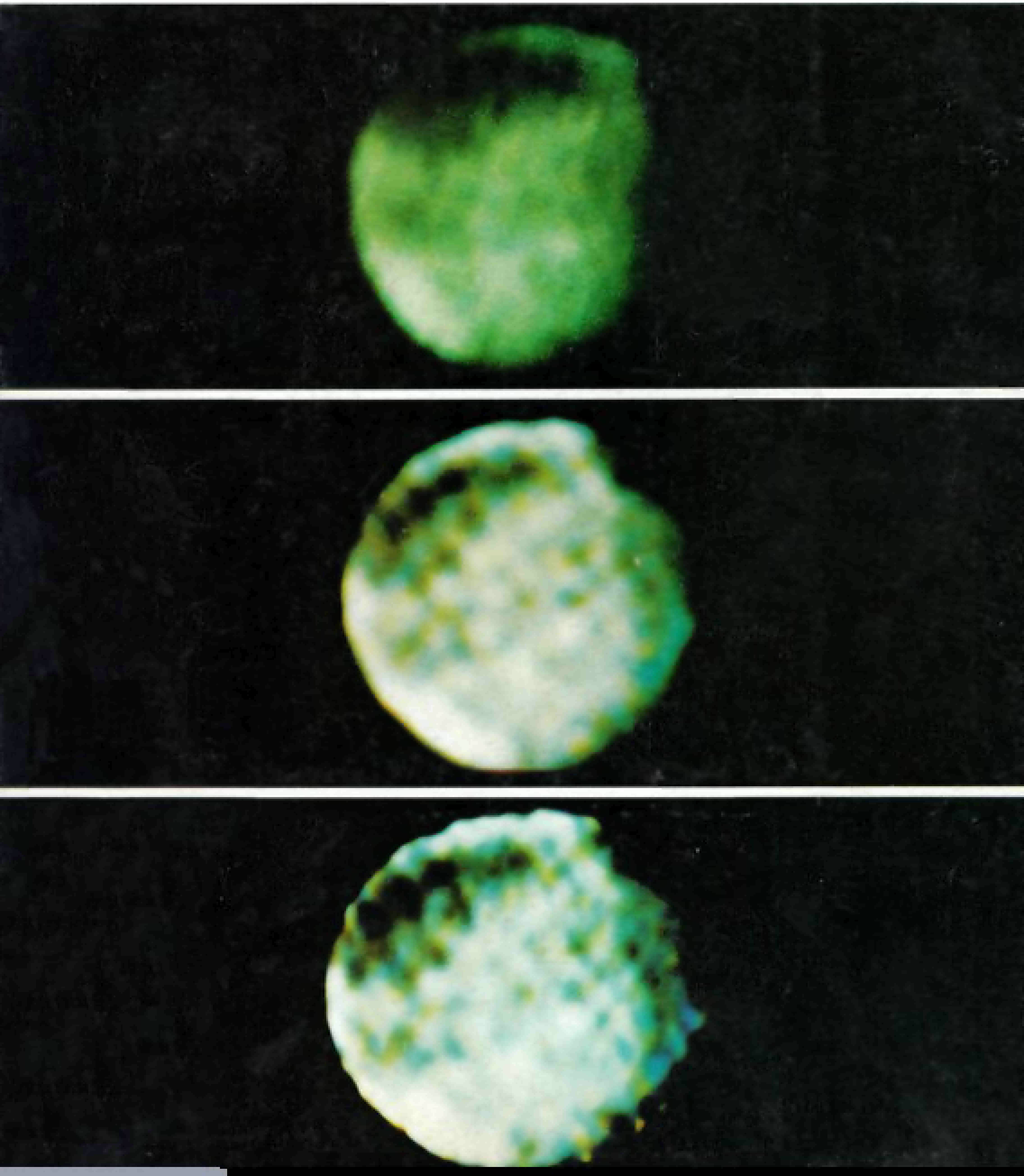


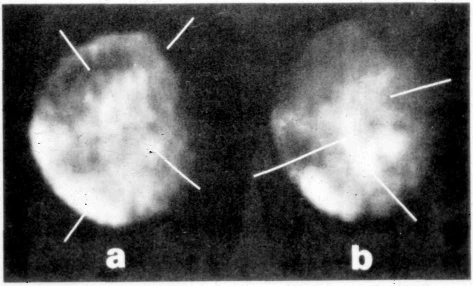


Fig. 3. Ganymede image data: (a) red channel, (b) blue channel. As a visual aid, the data have been developed with high photographic gamma, geometrically stretched, and linearly interpolated. The white pointers indicate key features that will show some interesting structure in the restorations to follow.

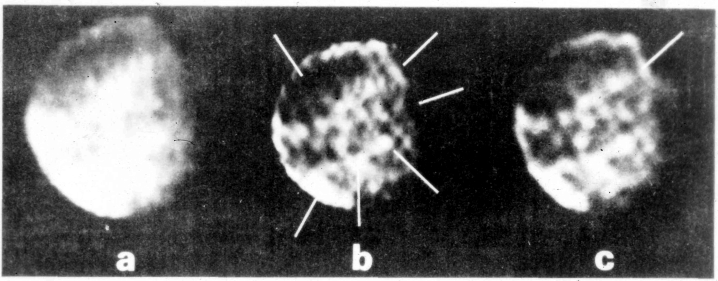


Fig. 4. Red channel image (a) and restorations by maximum entropy (b) and linear convolution (c). The pointers indicate enhanced versions of the key features pointed out in Fig. 3a.

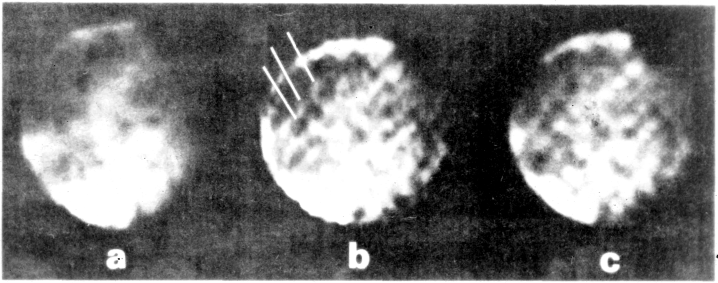


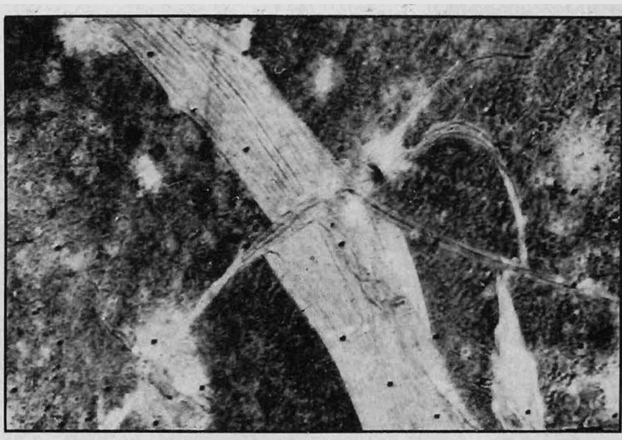
Fig. 5. Blue channel image (a) and restorations by maximum entropy (b) and linear convolution (c). The pointers indicate three mare-like features. The top one actually appears to show some internal structure. The bottom mare seems to intrude into the middle one, which is reminiscent of certain lunar maria.

Ganymede: A Bit of Everything

The largest of Jupiter's major moons also has the most complex terrain

BY JONATHAN EBERHART

Huge, dark spot on Ganymede (left) is probably ancient impact site. Parallel grooves appear displayed by transverse fault (right), suggesting tectonic activity (see map, 13° lat. *by −10° long.).*



Voyager 2/JPL

Viewed as art, the Galilean satellites of Jupiter comprise a diverse gallery. At one stylistic extreme is Io, a kinetic sculpture with its erupting volcanoes, ever-changing surface and manic coloration. At the other end is Callisto, a classic, almost idealized model of a cratered world, unblemished by mountains, valleys or other deviations from the theme. Between them is impressionist Europa, a pale sphere dashed with streaks so flat and intertwined that they look as though they might indeed have been applied with a paintbrush, if not as the abstract drippings of a Jackson Pollack. The other entry is giant Ganymede, larger even than the planet Mercury. And Ganymede is, well, dada.

Dictionary definitions of dada often invoke such terms as anarchistic or irrational, and Ganymede certainly appears in a subjective viewing to have been designed in defiance of the "rules." In some places it is smooth; elsewhere it is as tortured and craggy as the highlands of earth's moon, although even in the roughest spots the ups and downs of the terrain span no more than a few hundred meters. There are craters ringed by wide, bright haloes, presumably of ice overturned from the satellite's thick, frozen crust, yet others nearby in similar terrain show only slight traces of such borders. Most of the craters are relatively small, with few if any in the hundreds-of-kilometers range—except for a huge, dark spot, covering fully a third of its hemisphere and bullseyed with concentric rings, which almost surely resulted from a titanic impact that on a hardrock world would have resulted in a vast basin.

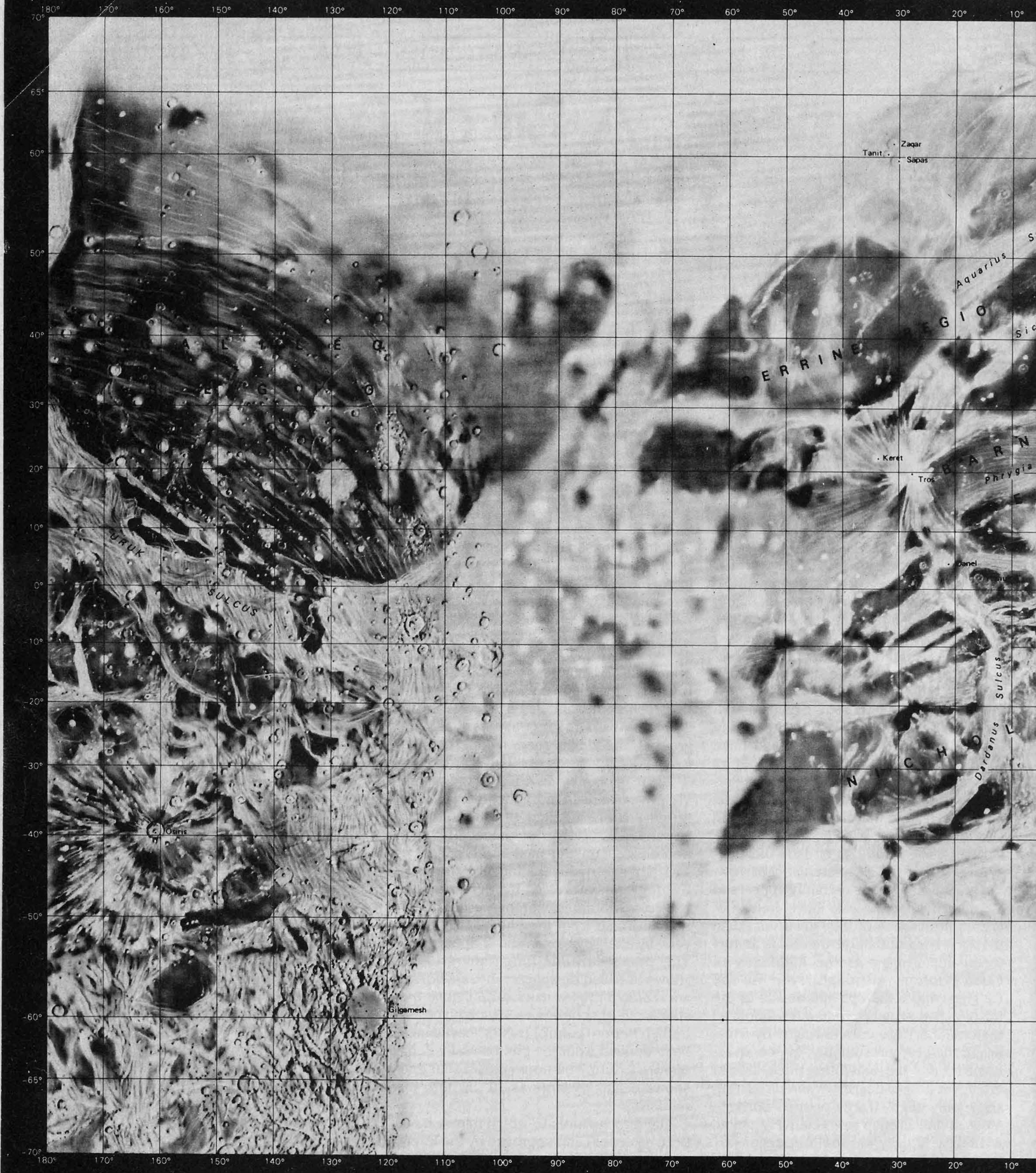
It is not diversity alone, however, that characterizes Ganymede's unusual appearance — Mars, for example, offers a wide-ranging host of terrain types. But Ganymede presents its various facades in what almost appear to be discrete sections, like a model assembled from a collection of mismatched parts. And creating much of that segmented appearance is Ganymede's most unusual feature: a global network of grooves and ridges, branching, weaving and intersecting in bizarre array. And many are not just single lineaments, but families in parallel, with some paths showing as many as 20 grooves and ridges running side by side for tens or hundreds of kilometers.

The map of Ganymede is a strange sight. Viewers have been moved to comparisons ranging from medical photographs to electron micrographs of almost anything. Reproduced on the next three pages, it was drawn by Jay L. Inge of the U.S. Geological Survey's Branch of Astrogeologic Studies, working with a hand-held airbrush from the photos taken last year by the Voyager 1 and 2 spacecraft. The map's latitude-longitude grid as shown is based on spacecraft trajectories and camera angles calculated before the spacecraft encounters ever took place, although better "control points" have since been derived from the photos and will be applied to future editions (the present grid shows errors as large as 10° in both directions).

The map features to which names have been assigned (and approved by the International Astronomical Union) are of three types: Broad areas, or *regiones*, are named for astronomers who discovered satellites of Jupiter. Crater names come from the legendry of ancient Middle Eastern cultures and from the Greco-Roman myth of Ganymede, one of the loves of Zeus (Jupiter). The same source of names has been used for the grooves or *sulci* (Latin for plowings or ditches).

But the existence of nomenclature and coordinates on a map does not mean that Ganymede's features are understood, particularly the grooves, which veteran astrogeologist Eugene Shoemaker of the USGS calls "one of the most aggravating, difficult, exasperating problems I've ever tried to solve." The patterns of the grooves seem to imply all sorts of tectonic activity in the satellite's past — twisting, sliding, stretching — but with a major difference from such activity on the earth. Missing on Ganymede, says Lawrence Soderblom of the USGS, are signs of emergence and subduction, in which new crustal material rises while old plates are driven into and beneath one another. A likely key is that Ganymede appears blanketed not in rock, but in hundreds of kilometers of ice. Solid rock is more dense than liquid magma, so earth's rocky plates sink, Soderblom says, but solid water — ice — will float on liquid water. Shoemaker believes the question is far more complex, possibly involving different "phases" of ice that can form under the tremendous pressure of great depth. A gram of "ordinary" ice, for example, occupies about 1.08 cubic centimeters, Shoemaker says, while a gram of more dense "ice-5," such as might exist several hundred kilometers beneath Ganymede's surface, occupies only about 0.76 cc. If changing temperature conditions prompted a deep ice-5 layer to change to ice-2 (0.86 cc/g) or ice-1, Ganymede's outer layers could have expanded enough to create cracks all over the satellite's surface. But high-pressure ice physics is a virtually new field to most planetologists (including, Shoemaker admits, himself), and Ganymede's surface was not even seen in close-up until 14 months ago. Stay tuned.

Next and last in the series: Callisto. □



Ganymede

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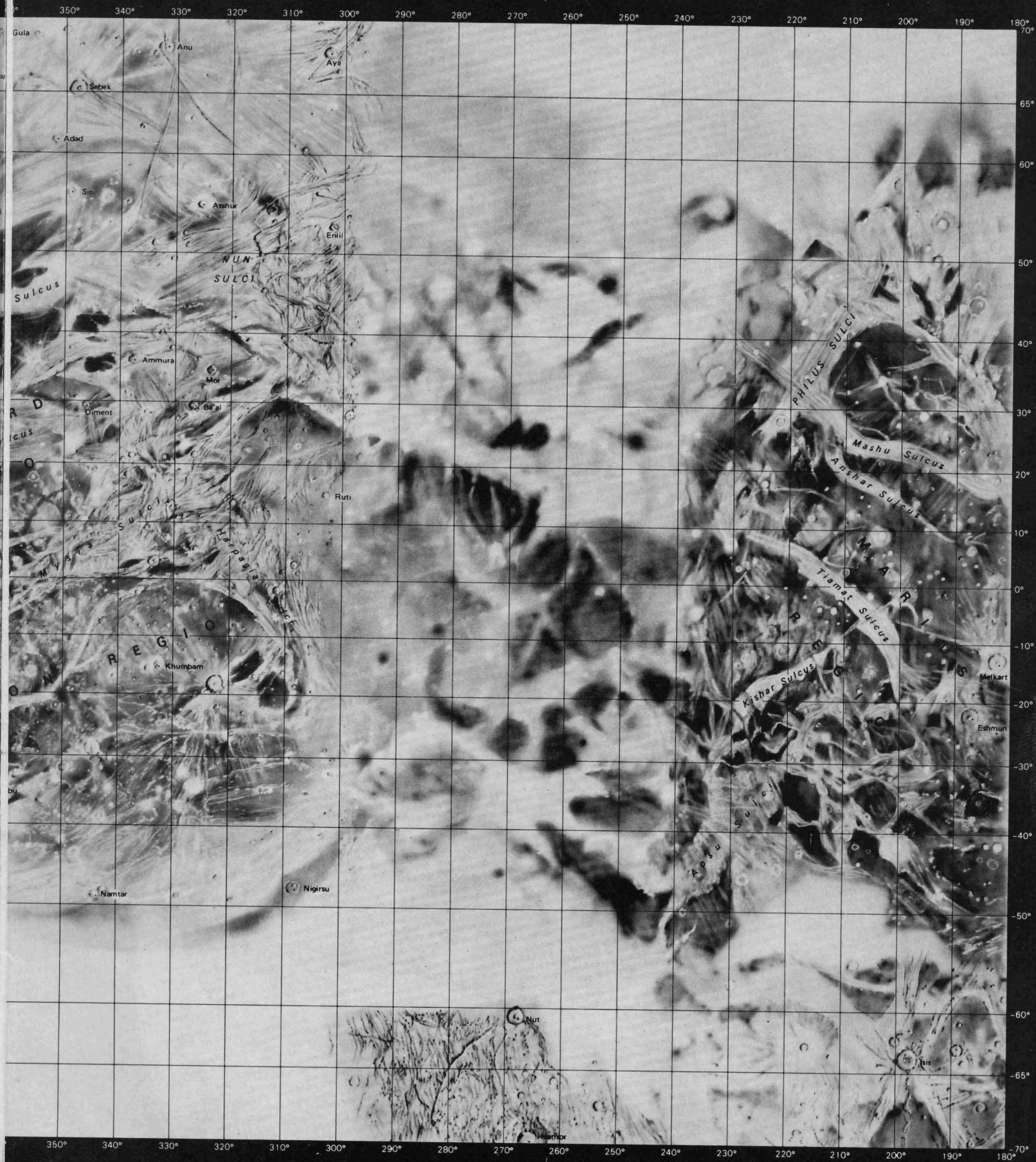
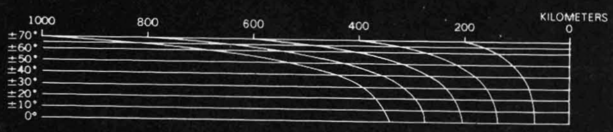
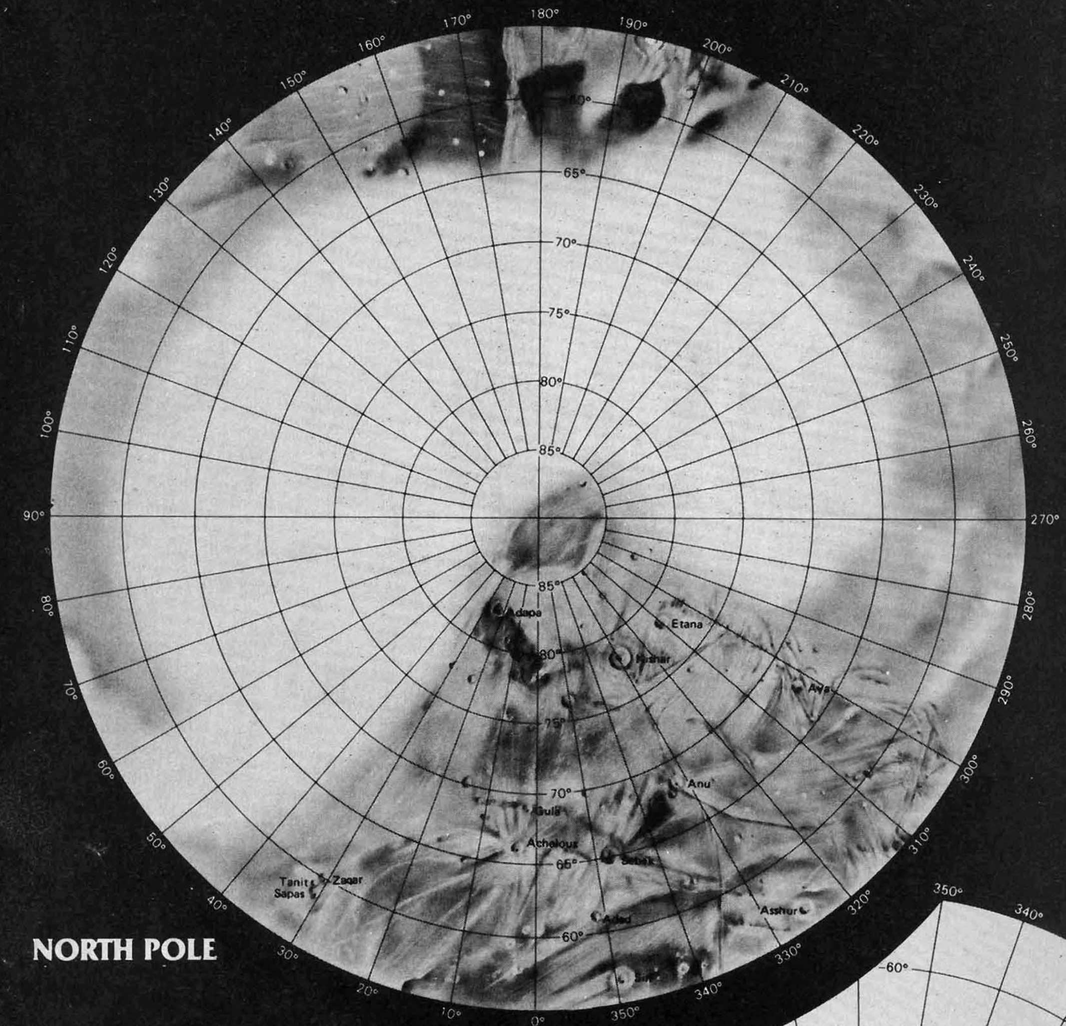


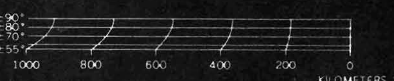
Map of Ganymede, largest of Jupiter's four Galilean satellites and second farthest from the planet, shows complex terrain with intersecting arrays of parallel grooves and ridges. Prepared from Voyager 1 and 2 photos by the U.S. Geological Survey's Branch of Astrogeologic Studies, map was drawn at 1:25,000,000 scale, reproduced here at 1:35,000,000. Diameter of Ganymede, refined in calculating latitude-longitude grid, is 5,276 ± 20 km.

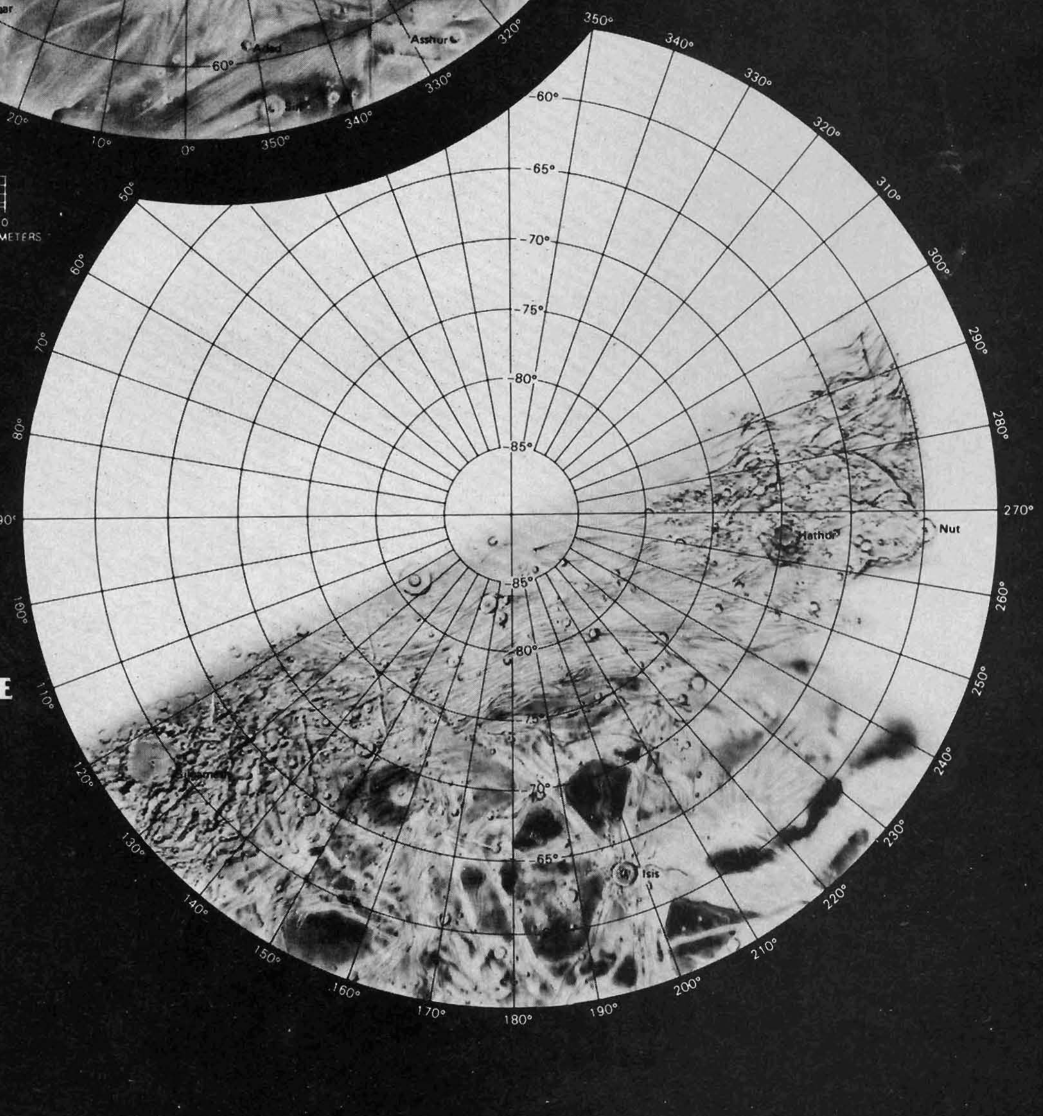


Ganymede is the only one of the Galilean satellites for which the Voyager spacecraft photos include portions of both poles. The parallel grooves, intervening smooth areas and heavily cratered terrain can all be found in the polar regions. The northern region's seeming smoothness, compared with the south, is in large measure due to the lower resolution of the photos from which the map was made.



NORTH POLE





SOUTH POLE