Global Analysis of Grooved Terrain Tectonics on Ganymede

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Funded by: NASA, 2004
Program: Outer Planets Research (OPR)

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Reprint attached

Summary of Personnel and Work Efforts

Commitment (fraction of year)	Year 1	Year 2
Geoffrey Collins	25%	25%
Undergraduate assistant	20%	20%

Scientific/Technical/Management Section

Introduction

The outermost Galilean satellites Ganymede and Callisto pose an intriguing dichotomy. They are similar in mass and radius, yet two thirds of Ganymede is covered with tectonic features known as grooves, while Callisto does not display any non-impact-related tectonic features. Gravity data from Galileo flybys of the two bodies show that the interior of Ganymede is highly differentiated (Anderson et al., 1996), while Callisto is partially undifferentiated (Anderson et al., 2001). Orbital evolution models of the Galilean satellite system show that Ganymede could have experienced increased tidal strain and heating in the past (Showman et al., 1997), while no such mechanism operated on Callisto. Perhaps such a tidal heating episode could have acted as a differentiation trigger for a partially differentiated Ganymede. Alternatively, the difference in differentiation states could be explained by a slow initial accretion of Callisto as compared to Ganymede (Mosqueira and Estrada, 2003).

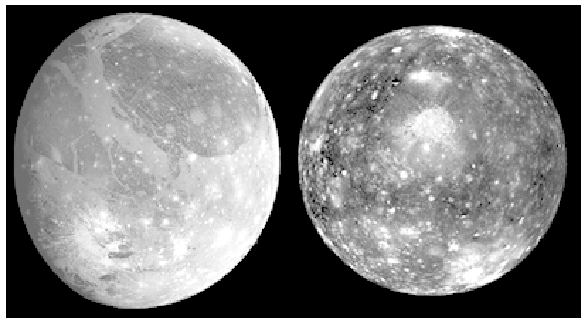

Figure 1: Global views of Ganymede and Callisto

It is tempting to assume that the stress that created the grooves on Ganymede is linked in some way to the satellite's tidal evolution or to the internal heating associated with differentiation, since such a linkage would help to explain the dichotomy, but we must find some way to test these hypotheses. We propose to compare the history of strain recorded on Ganymede's surface to theoretical stress models produced by differentiation, tidal, and rotational figure change, in order to search for a correlation between theory and observation.

The history of strain on Ganymede's surface is largely recorded in the form of grooved terrain. In the moderate resolution Voyager and Galileo gap fill images, grooved terrain appears as a collection of dark lineaments, occurring in bundles or packets (groove sets) oriented in different directions, and these groove sets crosscut each other (Figure 2). When crosscutting relationships are used to separate the groove sets by relative age in the Uruk Sulcus region, it can be seen that many of the sets share common orientations within their relative time periods (Collins et al., 1998a). At high resolution, the lineaments that make up grooved terrain appear to be almost all extensional features such as tilt-block normal faults or horst and graben sets (Pappalardo et al., 1998). Some transtensional and strike-slip features have also been found at high resolution (Pappalardo et al., 1998; DeRemer and Pappalardo, 2003), but no unambiguous evidence for contractional features has yet been discovered.

There are three reasons we are pursuing global stress models in this proposal, as opposed to stresses controlled by internal convection or localized mechanisms. First, global stress models are predictable, as several papers have explored the theoretical background for stresses due to changes in spin rate (Melosh, 1977), tidal recession (Melosh, 1980a), nonsynchronous rotation (Helfenstein and Parmentier, 1985), or polar

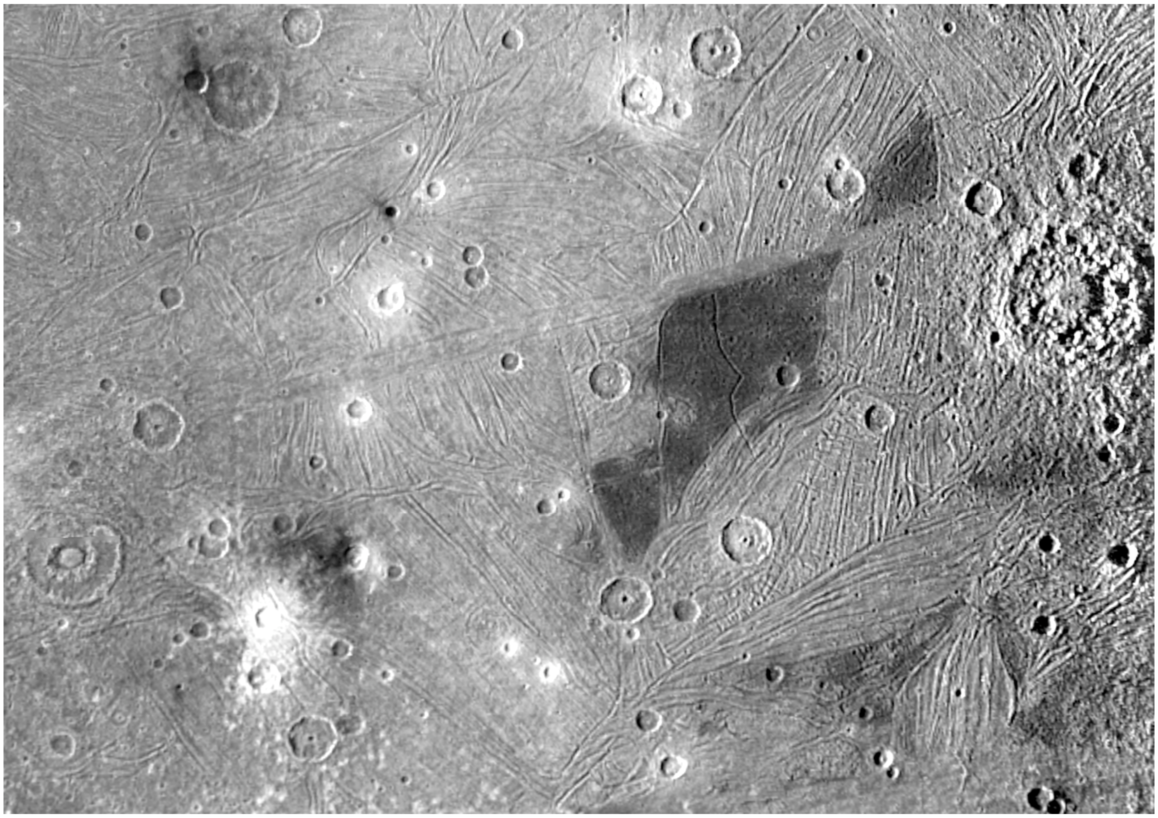

Figure 2: Grooved terrain on the leading hemisphere of Ganymede, imaged by Galileo in orbit C9. Width of image is 1300 km.

reorientation (Melosh, 1980b), and we should test the hypotheses that make rigid predictions for stress orientations before we examine more localized mechanisms. Second, some of the groove sets on Ganymede extend for thousands of kilometers, and orientations of similar aged grooves can be consistent over large areas, which argues against a highly localized mechanism for producing the stress pattern (Collins et al., 1998a). Third, hypotheses about global stresses on Ganymede have been proposed in the literature, and we can now test them. Murchie and Head (1986) proposed that Ganymede experienced tidal despinning followed by polar reorientation. Nonsynchronous rotation may explain the observed lack of a strong leading-trailing hemisphere asymmetry in crater density and the presence of catenae (presumably formed by split comets) on the antijovian hemisphere (Zahnle et al., 2001). Internal differentiation of Ganymede has been proposed as a mechanism for grooved terrain formation (Squyres, 1980; Mueller and McKinnon, 1988), and differentiation will produce a global stress pattern as the amplitude of tidal and rotational distortion decreases due to central mass concentration (Dermott, 1979). Volume expansion of Ganymede by heating (Showman et al., 1997; Zuber and Parmentier, 1984) or by differentiation (Squyres, 1980; Mueller and McKinnon, 1988) is also an attractive hypothesis for groove formation, as it allows large amounts of surface extension without the necessity for balancing contraction elsewhere.

Objectives and expected significance

The first objective of this project is to produce our best estimate of the global strain history of Ganymede, given the limitations of available data. This global strain history will show the orientation of strain recorded by the grooved terrain across the globe, the evolution of strain through time, and an estimate of the magnitude of strain. The second objective of the project is to compare this strain history to a variety of global stress models and combinations of global stress models, to find if there is any good correlation between the predictions of these models and the strain history recorded on Ganymede's surface.

This project is significant because the driving mechanism to create grooved terrain on Ganymede has been an unsolved problem since the Voyager encounters. Many papers have been written about grooved terrain for the past quarter century, and with the completion of a global image mosaic, we now have the ability to test some of the ideas from the literature. Addressing this issue can shed some light on the origin and nature of the Ganymede-Callisto dichotomy, which remains an important unresolved question in comparative planetology. Depending on the results from this project, it may also shed light on the dynamic processes as Ganymede was captured into the Laplace resonance, which may be significant for the Galilean satellite system as a whole.

Technical approach and methodology

As a test of theory by observation, the proposed work is facilitated by recent advances in both of these areas. Though the theory describing surface stresses induced by various figure change mechanisms has been in the literature since the 1980s, recent efforts to understand the pattern of ridges and bands on Europa have reinvigorated this field. Collaborator Pappalardo and his students have recently implemented a software tool called "Satellite Stress" that can change the position and amplitude of the tidal axis on Europa, so as to predict the surface stress field resulting from mechanisms such as diurnal tides and nonsynchronous rotation (e.g. Stempel et al. 2004). PI Collins is currently working with Pappalardo (through a PG&G grant to Pappalardo) to generalize this tool for any icy satellite, and include stress calculations due to changes to the polar flattening due to changes in spin rate, changes in the k Love number due to differentiation of the interior, polar wander due to reorientation of an unstable ice shell, and the effects of obliquity variations. For Ganymede, we wish to investigate driving mechanisms such as differentiation, nonsynchronous rotation, and polar wander. Differentiation is a particularly interesting process to investigate because is may combine the effects of lowered tidal and rotational distortion due to concentration of mass in the interior (Dermott, 1979), spin-up due to conservation of angular momentum, and resulting nonsynchronous rotation. The Satellite Stress program can take any combination of these effects and predict the resulting surface stress field.

The primary advance which makes this project possible is on the observational side, with the completion of a combined Voyager-Galileo image mosaic of Ganymede (Becker et al., 2001) covering 95% of the surface at moderate resolution (< 3.5 km/pixel). After the completion of the Galileo prime mission and the production of the first global image mosaic, PI Collins created a global database of all grooves on Ganymede visible in the global mosaic (Figure 3; Collins et al., 2000). This database was created using a Geographic Information System (GIS), and includes over 61,000 features. For the purposes of this database, grooves are defined as any topographic trough within or adjacent to bright terrain, which is not part of an impact structure. The database is composed of georeferenced line segments which lie along the bottoms of the troughs. At high incidence angles, the troughs are directly observable by shading, while at low incidence angles is was found through high resolution images that the darkest part of the lineaments correspond to the bottoms of the troughs (Collins et al., 1998b). The groove database serves as the basis for our proposed work, outlined below.

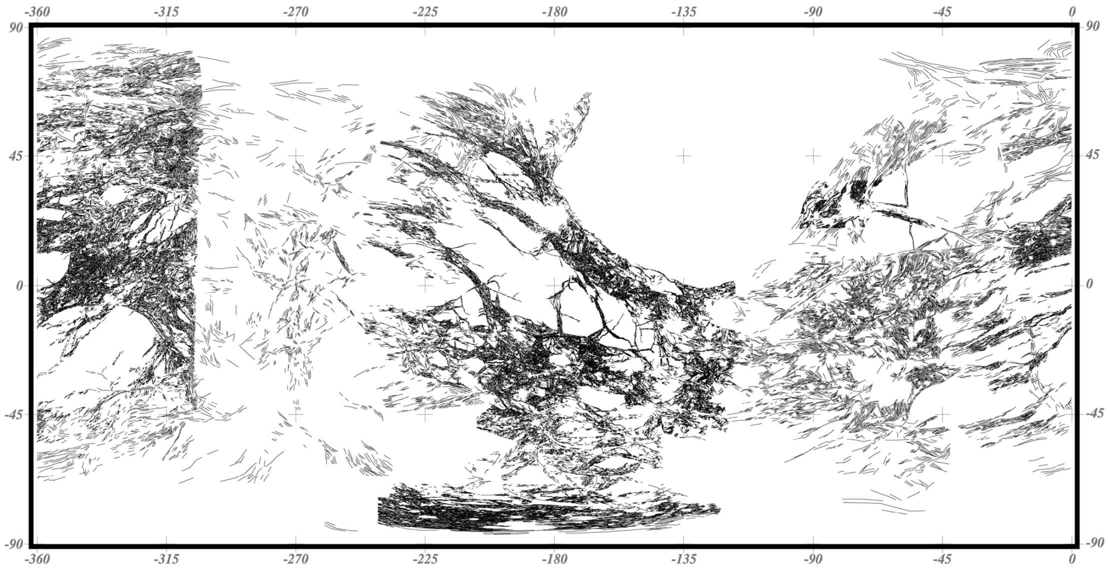

Figure 3: Simple cylindrical map of Ganymede showing all grooves currently in the database. The marked discontinuity at ~310° W is due to a jump in resolution from Galileo E6 gapfill data to near-terminator Voyager 1 coverage.

Task 1: Revise and refine groove database

After the production of the global groove database, Galileo completed two additional flybys of Ganymede during the Galileo Millennium Mission, on orbits G28 and G29. These additional flybys provided new image data of Ganymede's surface, which triggered a revision of the global image mosaic to include the new data. During this revision the coordinate control network was improved (Becker et al., 2001), which led to a shift of all the Galileo and Voyager image data with respect to latitude and longitude. Since the groove database was mapped before this coordinate revision, the location of the grooves in the database no longer perfectly matches up with the grooves in the current global image mosaic. Therefore, the first part of task 1 is to revise the database to reflect the improvement in coordinate control. This will involve overlaying the database on the most recent image mosaic and shifting the location and angle of the mapped grooves until the database and image mosaic line up once again. Since the grooves within a particular region have all been shifted in the same direction, this task does not have to be performed individually for every single groove in the database, but different regions must be shifted in different directions.

The second part of task 1 is to revise the areas of the database where new imaging data has been acquired during orbits G28 and G29. Two of the regional-scale observations from G29 are especially important in this respect, as they cover areas within the Voyager 1 coverage which were compromised (from a mapping perspective) due to high emission angle or image smear. Groove structures which are now visible in the new data will be added to the database, assuring that it is as complete as possible given all of the imaging data collected of Ganymede by Voyager and Galileo.

The final part of task 1 is a quality assurance step, in which all the members of the team will carefully comb through the groove database and the most recent global image mosaic, searching for unmapped or mismapped structures. After the completion of task 1, we feel confident that the groove database will be the best representation of structures on Ganymede, and we can then make it available as a useful resource to other scientists (as a supplement to a publication and/or distributed through a web site such as PIGWAD at USGS - Flagstaff).

Task 2: Sort groove database into time sequence

Since there are relative age differences among groove sets, they cannot all have been formed at the same time under the same stress regime. Because we see grooves crosscutting each other at a variety of angles, no single stress pattern can be responsible for forming all of the grooves. In order to make a valid comparison of observation to theory, we need to separate the groove database into a time sequence, so that we can compare a theoretical driving stress to a set of grooves that could plausibly have formed within the same time interval.

Following the reasoning from high resolution Galileo images presented in Collins et al. (1998a; reprint attached), we will use cross-cutting relationships to determine the relative age between two groove sets, with the cross-cutting grooves being the younger of the two sets. Collins (2002) used this method to separate all of the youngest grooves from the database, since the youngest grooves are not crosscut by any other grooves. By finding the groove sets cut only by the youngest grooves, one can take another step back in the time sequence, then find the grooves cut only by the first two sets, and so on until all of the groove sets have been classified into relative age categories.

Manually keeping track of the age relationships of hundreds of groove sets in a region is a daunting task, but it is possible to slowly and methodically disentangle the relationships (McBee and Collins, 2002; Collins et al., 1998a). Time sequence disentanglement is also an issue on Europa, and has been accomplished for limited numbers of ridges (Figueredo and Greeley, 2004) or in small target areas (Kattenhorn, 2002; Sarid et al., 2004). The PI is currently working with collaborator Pappalardo (through a PG&G grant to Pappalardo) to develop a software tool for computer assisted time sequence sorting on Europa. This software tool works by keeping track of the relative age relationship between each pair of crossing lineaments, and then finds the sequence of lineament formation that fits the observed local relationships. The time sequence sorting program can easily be adapted to work on Ganymede, with the only difference being that it works with individual ridges on Europa, while we wish to classify groups of related lineaments (groove sets) together on Ganymede. The resolution of the images or the geometry of the groove intersections will sometimes make the age relationships ambiguous, which could possibly result in a loop in the chain of age relationships. Our sorting program will alert us to such loops, allowing us to break them at the weakest link - which is the most ambiguous cross-cutting relationship in the loop.

Task 3: Estimate strain across grooved terrain

In order to convert a collection of lineaments into a strain history, we must know what type of strain the lineaments represent. In the high resolution target areas imaged by Galileo, almost all of the grooves appear to be extensional structures. There are three

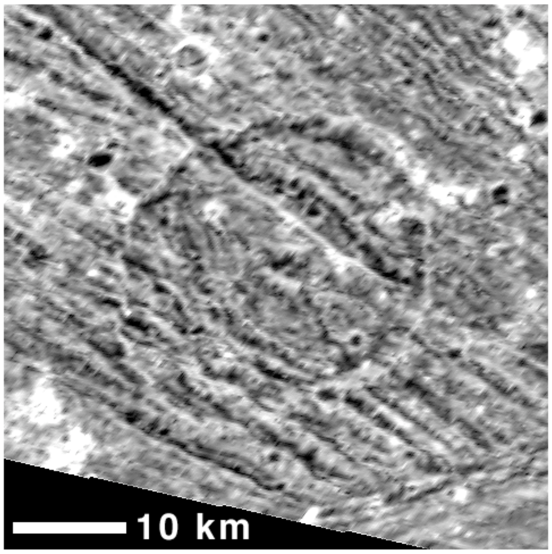

Figure 4: The moderately strained crater Nefertum has been extended by 15% by the grooves in Nun Sulci (Pappalardo and Collins, 2003).

basic morphological classes of grooves at high resolution: subdued dark lineaments, high relief sawtooth ridges, and smooth linear features. The subdued lineaments appear to be tension fractures or narrow graben at high resolution (Pappalardo et al., 1998), and analysis of craters cut by similar features shows that they exhibit at most a few percent extensional strain (Pappalardo and Collins, 2003). The high relief ridges and troughs often have a sawtooth cross-section, typical of tilt-block normal fault complexes (Pappalardo et al., 1998), and measurements of the fault geometry (Collins et al., 1998b) and craters cut by these faults (Figure 4; Pappalardo and Collins, 2003) show that they exhibit extensional strain of tens of percent. Smooth linear features may be formed by cryovolcanic flooding (Schenk et al., 2001), or possibly by plate separation and strike-slip motion, akin to bands on Europa (Head et al., 2002). General statements about the strain represented by smooth linear features is not possible at this point since different high resolution images of these features yield different answers. Until we better understand the origin of smooth linear features, we should leave them out of the strain history. Thus the first part of this task is to separate the smooth linear features out of the groove database before comparing it to the stress models. A few narrow groove sets also show evidence for transtension or strike-slip motion at high resolution (Pappalardo et al., 1998; DeRemer and Pappalardo, 2003), and these lineaments should also be separated out. Most of the groove types at high resolution show evidence for extension; no unambiguous contractional features have been found. We assume, therefore, that the vast majority of grooves in the database are extensional features, and that they strike perpendicular to the least compressive horizontal stress orientation (i.e. parallel to most compressive stress).

The second part of this task is to estimate the magnitude and orientation of extensional strain accommodated by the grooves during each time interval. Strain appears to correlate with morphology at high resolution, so separating the grooves in the database into morphological classes will help us to derive a strain estimate across larger areas of grooved terrain, or indeed around the entire globe. The PI and both collaborators are currently mapping the morphology of grooved terrain as part of a 1:15M global mapping project (funded by a PG&G grant to Head), and these morphological classes can be overlaid on the groove database and used to assign classes to individual groove sets. The importance of this large scale strain estimate is that different models for the origin of global stress patterns on Ganymede predict different amounts of strain, so this strain estimate can be used along with the stress model comparison in task 4 to find the best fit driving mechanism for grooved terrain formation.

Task 4: Compare stress models to observed groove patterns

With the groove database finalized, sorted into a time sequence, and analyzed for the strain direction and magnitude in tasks 1 through 3, we will have a best approximation to the strain history of Ganymede from currently available data. With the Satellite Stress program, we will have a way to calculate the stresses induced by a variety of different mechanisms, to test various models for global stress patterns on Ganymede, as outlined in the introduction. The pinnacle of this project is to put these two strands together, and compare theory to observation.

To accomplish this, a small amount of setup and computer programming is required, followed by a lot of processing by the computer. For each relative age unit in the groove database, a GIS routine will geographically split the database into a series of small blocks, perhaps 10° on a side, and then produce files with lists of the azimuth and length of each groove segment in each of these small blocks. We will then use the Satellite Stress program to loop through many different combinations of figure change in different axial orientations, predicting the azimuth of most compressive stress for each combination in each small geographic block. A final program will then compare the predicted azimuth to the actual azimuths of groove segments in each block, and compute the correlation between these two azimuths, with the contribution of each groove segment to the correlation weighted by its length. The weighting will suppress the possibility that wiggly grooves with many short segments would count more than long straight grooves with fewer mapped segments. The program will output tables of correlation coefficients for each run, allowing us to search the parameter space of figure change combinations and orientations for the best fit to the observed groove pattern. Preliminary versions of all of these programs are already operational, and a version of the approach limited to combinations of differentiation stress and nonsynchronous stress has been tested on the youngest grooves in the database (Collins, 2002). The results of this preliminary analysis shows that the youngest grooves are most highly correlated to stress caused by differentiation without nonsynchronous rotation, with the tidal axis oriented 70° east of its current position. A close second in the preliminary study was stress from the last 60° of nonsynchronous rotation.

Assuming that we find good correlation between theory and observation for each time interval, the next step would be to examine the results for the time intervals together to determine the most likely sequence of events to create grooved terrain. For example, if the only mechanism which shows high correlation through all the time steps is nonsynchronous rotation, and there is a systematic drift of the tidal axis through time as this rotation proceeds, then this would be good evidence that nonsynchronous rotation is an important driving mechanism for controlling the orientation of structures in grooved terrain, and that Ganymede went through a period of nonsynchronous rotation during the period of groove formation.

Another important factor to consider when evaluating the most likely driving mechanisms is the fact that, though the models assume an elastic ice shell, a viscoelastic response is a closer approximation to the behavior of the ice, so stresses cannot build up over hundreds of millions of years without creeping away. Thus, it will be important when examining a candidate model for grooved terrain formation to compare the timescale over which that model operates to the Maxwell time of the upper part of the ice shell. For example, if stress due to differentiation appears to be important, the Maxwell time could be compared to the timescale of stress buildup on the crust due to differentiation (which could be as fast as 1000 years in a runaway event; Friedson and Stevenson, 1983).

Task 5: Submit work for publication

The final task of this project is to prepare and submit a manuscript describing the groove database, the results of classification of the database by relative age and strain, and the correlation between the strain history recorded on Ganymede and theoretical stress patterns produced by various figure change mechanisms.

Impact of proposed work on state of knowledge in the field and relevance to NASA programs

Constraining the possible driving mechanisms for grooved terrain formation on Ganymede will help us to understand the origin of the Ganymede-Callisto dichotomy, and the evolution of the Galilean satellite system. Stresses induced by differentiation or figure change have been previously proposed for Ganymede, and we will test all of these hypotheses and more. The groove database and the strain history that we derive for Ganymede will represent the best information from available data, and will serve as a resource for further investigation of grooved terrain tectonics until better data can be obtained by the Jupiter Icy Moons Orbiter.

The only previous large-scale attempt to quantitatively analyze the global pattern of grooves on Ganymede was by Bianchi et al. (1986), who plotted great circle poles for about 9800 groove segments from the Voyager data. They found two concentrations of great circle poles, and interpreted this pattern to be the result of global-scale equatorially-symmetric convection cells. Our database contains 20 times the number of groove segments, and it is global in nature rather than confined to the two Voyager regions. Though we have found one of the concentrations of poles described by Bianchi et al., we have found other patterns in the data that their analysis does not account for. By comparing the database to a variety of global stress mechanisms, we hope to make sense of these patterns.

In this work, we will be developing and testing a suite of tools for comparing mapped lineaments to a variety of tidal, rotational, and differentiation stress mechanisms. These tools are also currently being applied to Europa, and could be applied to tectonic features on any satellite. In the near future, we can apply these tools to Cassini imaging data for Saturnian satellites such as the grooves on Enceladus and "wispy terrain" on Dione, which is probably a region of faulted ice. It is possible that the system of ridges on Triton may reflect its orbital evolution around Neptune (Collins and Schenk 1994), so if the strain across ridges on Triton could be determined, we could also apply these tools there. It is also possible that tectonic features could be formed on the surfaces of Pluto and Charon by tidal and rotational distortion (Collins and Pappalardo, 2000), depending on the original distance between the bodies before they evolved out to their current tidally locked state. If such features are found when New Horizons arrives at Pluto and Charon, we can use the tools developed in this project to constrain the orbital evolution of this binary planet system.

The proposed work addresses all of the objectives of the Outer Planets Research program. It enhances the scientific return from the Galileo and Voyager missions by refining a global database of grooves on Ganymede based on Galileo and Voyager imaging data. It improves our understanding of the evolution of outer planet satellites by testing theoretical models for differentiation and figure change on Ganymede against the record of grooves on its surface. It addresses the orbital dynamics of the Galilean satellites by searching for evidence that these dynamical processes have left their mark on the surface of Ganymede. This proposal addresses NASA's strategic goal of exploring the solar system, and the science objective of learning how solar system bodies have evolved into their diverse states, specifically in the research focus area of studying the processes that determine the characteristics of bodies in our solar system.

Plan of work

In year 1, we will complete task 1 (revise the database) and most of task 2 (sort grooves by age), which is the longest task. We will finish task 2 early in year 2, and then complete task 3 (estimate strain). Midway through year 2, with tasks 1 through 3 finished, we will have the input data ready to analyze, at which point task 4 (compare grooves to theoretical stress patterns) will be accomplished. Finally, task 5 (prepare work for publication) will be primarily concentrated in year 2, with submission of a manuscript for publication in the latter part of year 2. In each year, we will also present our findings at a major international conference.

PI Geoffrey Collins was involved with the Galileo Solid State Imaging team from 1995 until Galileo's demise in 2003, planning image sequences for targets on Ganymede and Europa, and performing extensive research on Ganymede grooved terrain. He will be responsible for performing the tasks in all phases of this project, supervising the undergraduate assistant, and will be frequently communicating with the collaborators over email. In both years of the project he will travel to Boulder, Colorado to consult with collaborator Pappalardo, and he will often make the short drive to Providence, Rhode Island to consult with collaborator Head. Dr. Collins is currently an Assistant Professor of Geology at Wheaton College, a private undergraduate liberal arts college in Norton, Massachusetts.

Wheaton places a high value on faculty-student collaboration in scientific research, and we propose to hire an undergraduate student to assist in this research project. In the first year, the undergraduate assistant will primarily assist the PI with the revision of the groove database and check for any errors between the mapped grooves and the most recent global image mosaic. Toward the end of the first year, the assistant will begin to help the PI assign groove sets to different time categories. In the second year, the assistant will help the PI to finish assigning groove sets to time categories, and then will work on assigning some groove sets to morphological categories in support of the strain estimate.

Collaborator Robert Pappalardo has been instrumental in providing detailed structural interpretations for the deformation seen in high resolution areas of Ganymede grooved terrain. He will provide the Satellite Strain software originally developed by his research group for examining tidal deformation on Europa, and which we are currently modifying for use in calculating deformation on Ganymede. Pappalardo and Collins are jointly developing time sequence sorting software for Europa that will serve as the basis for the time sequence sorting software to use on Ganymede groove sets. They have also recently collaborated on calculating the strain in local areas of grooved terrain on Ganymede, and Pappalardo will consult on the strain calculations in this project.

Collaborator James W. Head has been leading post-Galileo mapping efforts on Ganymede at the local and global scales, and has published several papers on Ganymede geology over the past two decades. He will assist the PI in assuring the quality of the mapped database, and in linking the groove database to the overall geological mapping effort on Ganymede. Drs. Collins, Pappalardo, and Head have worked together on Galileo SSI targeting of Ganymede and Europa, and have collaborated on several successful research projects in the past.

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Facilities and Equipment

This work will primarily be performed at the Planetary Mapping Lab at Wheaton College, which houses computer equipment well-suited for performing the tasks outlined in this proposal. The lab includes both Windows and Macintosh workstations with large monitors, large hard drives, and CDR - DVD drives, linked over a high speed network with printers, a scanner, and a large-format printer. The computers run software suitable for this project, including ArcGIS, Visual C++, ENVI, and Photoshop. All of the Galileo and Voyager image data needed for this project is already loaded on the computers.