FINAL TECHNICAL REPORT

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Fracture and Stress Evolution on Europa: New Insights Into Fracture Interpretation and Ice Thickness Estimates Using Fracture Mechanics Analyses.

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Preamble

This report serves as the final technical report for the above mentioned project. The grant period began on January, 1, 2002 and finished on June 30th, 2004.

The project personnel consisted of the PI, a co-investigator who served in an advisory capacity, and two full-time graduate students who completed MS thesis projects funded by the grant. The project ultimately led to the development of 6 full-length papers (1 published, 1 in press, 2 accepted/in revision, and 2 in preparation), 9 conference presentations with abstracts, and 1 invited seminar presentation at the Lunar and Planetary Institute in Houston, Texas.

The success of the project, as outlined below, has enabled the strengthening of the planetary geoscience research program in the Department of Geological Sciences at the University of Idaho. I have successfully competed for two additional grant awards through the NASA-Idaho Space Grant Consortium and NASA-EPSCoR, and have developed national recognition through collaborations and interactions with numerous peer researchers. Furthermore, my planetary geoscience research program now attracts several graduate student applicants per year and has acquired two additional current graduate students working on research projects (one as an MS thesis and one as a PhD dissertation). A follow-up grant proposal is pending at NASA PG&G.

Project Goals and Accomplishments

Each of the general goals of the project, as stated in the original proposal, has been successfully completed. The individual goals are presented below, followed by a synopsis of the accomplishments for each goal.

<u>Stated Goals:</u>

(1) To unravel the surface stress history on Europa and explain fracture orientations in the context of either global tidal stress models or locally perturbed stress fields related to pre-existing features such as strike-slip faults. Consequently, estimate the amount of nonsynchronous rotation experienced by the ice shell of Europa.

(2) To identify and mechanically analyze strike-slip faults on Europa, describing their displacement characteristics, and modeling the nature of the perturbed stress fields around them.

(3) To examine the evolution of cycloidal ridges in the context of strike-slip mechanical models that treat cycloidal ridges as slipping interfaces.

(4) To provide constraints on the thickness of the Europan crust using fracture spacing relationships and ice crust bending characteristics, and to determine potential locations for crust-penetrating fractures that may provide access to an underlying ocean.

Accomplishments in each goal:

(1) Unraveling tidal stress history and amount of nonsynchronous rotation

The purpose of this goal was to examine the various types of fractures (lineaments) on the surface of Europa and to place the formation of these fractures into the context of the stress fields that produced them. Hence, the temporal evolution of the stress field could be reconstructed and then interpreted through comparison to global tidal stress models as well as linear elastic fracture mechanics based models of perturbed stress fields around pre-existing lineaments. This aspect of the study resulted in 1 published paper and 2 conference presentations.

Previous analyses of fractures on Europa have typically invoked global scale stress fields, caused by diurnal tidal stresses or nonsynchronous rotation stresses, to explain fracture development and fracture orientations. This study has produced evidence to indicate that many fractures on Europa are the result of secondary fracture development in the perturbed stress fields adjacent to active strike-slip faults, or due to bending-induced stresses alongside prominent ridges that create a topographic load on the ice shell. These secondary fractures can be up to hundreds of kilometers in length. In essence, the development of such features in the Europan shell highlights the importance of correctly identifying the likely driving force behind the creation of lineaments so that each feature can be correctly interpreted in the context of the stress field history. The existence of certain fracture orientations within the overall fracture sequence that, in global stress models, require the passage of large periods of time between successive fracture events before a nonsynchronous rotation stress field exists that is compatible with the observed fracture orientation, results in large overestimates of the total amount of nonsynchronous rotation if global tidal stress models are adopted indiscriminately. If such anomalous fracture trends are discovered in a fracture sequence analysis, it is concluded that the driving force behind such fractures needs to be determined unambiguously to rule out the possibility of a genetic relationship with an active pre-existing structure (such as a strike-slip fault) before global tidal stress models are applied to explain their development.

A nonsynchronous rotation estimate was determined through detailed mapping and fracture sequence reconstruction near to Conamara Chaos (a project that began before the start of the funding period for this project). Every attempt was made to distinguish fractures created by stresses induced by nonsynchronous reorientation of the tidal bulges in the ice shell (the dominant driving force for fracturing) from stresses caused by local perturbations by pre-existing features. For example, some fractures were clearly the result of bending alongside prominent ridges. The analysis revealed a consistent clockwise rotation of stresses through time, compatible with previous models that related such temporal variations to nonsynchronous rotation effects. The fracture and stress analysis indicated at least 720° of nonsynchronous rotation of the ice shell about its stable interior. Anomalous fracture orientations within the fracture sequence, particularly in the most recently formed fractures, place some degree of uncertainty on this estimate, and imply a higher possible amount, as much as 900°. The fractures in question could not unarguably be differentiated from those having developed by bending-related stresses or due to locally perturbed stresses; therefore, the uncertainty in their characterization indicates that only the 720° estimate is reliable.

Nonetheless, this analysis raised many new issues that place some doubt on this and all previous estimates of nonsynchronous rotation. A recent published model hypothesizes that much of the fracture formation on Europa may be the result of shear failure. If this is the case, then multiple fracture orientations could potentially develop within a single stress field. In the Conamara Chaos study area, a shear origin for fractures could result in a reduced total nonsynchronous rotation estimate by as much as 180°, for a total of 540°. Although I have found no evidence in support of a shear failure mechanism for fracture development, with only a limited number of fractures showing evidence of strike-slip motions that apparently post-date fracture formation, this observation could be an image resolution issue. Certainly, the existence of numerous seemingly conjugate fracture orientations is troubling for a tension model assumption for fracture development (as was adopted in this and previous studies that estimated nonsynchronous rotation). I assert that a more comprehensive analysis of tensile versus shear failure mechanisms for fracture formation on Europa is needed to ensure that all future fracture analyses on Europa are undertaken with a clear understanding of the mechanics of formation of various fracture types. I have proposed a new study along these lines in a proposal submitted to the PG&G program in May 2004.

(2) Mechanical Analysis of Strike-Slip Faults

The purpose of this goal was to examine potential secondary fractures associated with strike-slip faults (specifically tailcracks at the tips of these faults) to determine the implications of such fracturing for unraveling details about strike-slip fault mechanics, as well as for demonstrating the direct applicability of linear elastic fracture mechanics (LEFM) theory to Europan fracture analyses. This aspect of the study resulted in 2 full-length papers (1 currently in press and 1 in preparation) and 3 conference presentations.

Several previous studies have noted the existence of tailcrack-like features at the ends of prominent strike-slip faults, such as Agenor Linea and in the Argadnel Regio ("Wedges") region; however, the significance of tailcracks for unraveling details of fault history have not been addressed. Tailcracks are secondary fractures, meaning they are a direct consequence of perturbations to the near-tip stress field in response to motions along a fault. Their locations and orientations are thus not controlled by global tidal stresses but rather by the mechanics of the fault motions. Tailcracks are common features along faults and other slipping interfaces (such as slipped joints and bedding planes) on Earth. LEFM theory has been successfully applied to terrestrial tailcracks, indicating that analytical solutions exist to describe the stress field at the tip of a slipping fault. For example, faults whose surfaces remain in contact during slip commonly produce tailcracks that make an approximately 70° angle with respect to the fault that created them. This angle is explicitly predicted by LEFM theory.

During this project, a survey of strike-slip faults across Europa indicated that tailcracks are significantly more common than has been previously recognized. Furthermore, the geometry of tailcracks varies in a systematic way as a function of fault morphology. Specifically, faults that resemble ridges produce high-angle tailcracks (commonly around 70° but with a median angle of 53°) with curving geometries very reminiscent of terrestrial tailcracks. In contrast, tailcracks at the tips of faults that are band-like typically form at smaller angles to the trend of the fault that produced them (mean tailcrack angle of 30°) and with curving geometries that are very different to terrestrial tailcracks in that the sense of curvature is reversed with respect to ridge-like fault tailcracks. Seeing as tailcrack geometries are explicitly controlled by the perturbed near-tip stress field, and that this stress field is a direct consequence of the specifics of fault motion, the differing tailcrack geometries imply a different mechanical behavior for ridge-like and band-like faults.

To address this hypothesis, the stress fields adjacent to Europan strike-slip faults were modeled using linear LEFM solutions and the orientations of fractures were determined that would be expected to develop in such stress fields. A range of mechanical behaviors were tested, ranging from faults whose surfaces remain in contact during fault motion to those in which a significant amount of dilation occurred during the slip phase. The rationale for testing the affect of fault opening during sliding is that diurnal tidal stresses are commonly tensile and would promote fault dilation, as outlined in the previously published tidal walking theory of fault motion. Our predicted tailcrack orientations for different mechanical behaviors showed a remarkable similarity to observed features on Europa, including adjacent to some of the larger strike-slip faults such as Astypalaea Linea and Agenor Linea. Of particular significance, our model results imply that band-like faults on Europa must have undergone contemporaneous dilation and shearing, resulting in reduced tailcrack angles and potentially allowing faults to access and extrude deep material (either from a sub-ice ocean or deep, ductile ice), resulting in faults having a banded appearance. This fault behavior is compatible with, and possibly an indirect confirmation of, the viability of the tidal walking theory. In contrast, ridge-like faults undergo little or no dilation during shearing, producing tailcracks analogous to terrestrial examples and disallowing the creation of bands. In this type of fault behavior, frictional shear heating along the fault walls may promote ridge building as buoyant shear-heated material moves upwards along the fault plane.

The tailcrack analysis has thus revealed an important range of mechanical behaviors of Europan strike-slip faults that not only resulted in disparate fault morphologies but also tailcrack geometries. Furthermore, the results of the analysis imply that tidal walking theory may only effectively describe the development of band-like faults but that ridge-like faults develop through some other, as yet undetermined, mechanism. Finally, the analysis has provided a convincing demonstration of the efficacy of LEFM theory for making quantitative predictions of fracture development and behavior on Europa.

Our analyses of secondary fracturing on Europa were augmented with the inclusion of a terrestrial analog geological mapping study of secondary fracturing along the Lake Mead strike-slip fault system in Nevada. This work was not funded by the current grant (additional funding was acquired from NASA-EPSCoR); however, the work was undertaken as a direct complement to the current project and provided important insights to perturbed stress fields around large-scale strike-slip faults. In particular, the similarity between terrestrial tailcrack geometries and those associated with ridge-like strike-slip faults on Europa was witnessed firsthand.

(3) Analysis of Cycloidal Ridge Growth Mechanics

The purpose of this goal was to revisit the topic of cycloids (or flexi) on Europa, which were previously explained by a single, all-encompassing model involving tensile cracking in the rotating diurnal stress field. Our goal was to locate evidence that specifically identifies the mechanics of the growth process, particularly the formation of cusps between individual cycloid segments. This aspect of the study resulted in 2 full-length papers (1 currently in revision and 1 in preparation) and 2 conference presentations.

The existing model for cycloid development identified the constantly rotating diurnal tidal stresses as the driving stress for cycloid growth, which we did not wish to dispute in the current study. From a fracture mechanics standpoint, however, the existing model is overly simplistic in that it does not account for different cycloid surface morphologies or their range of geometries (curvatures), ostensibly because it fails to examine the effect of rotating tidal stresses on the already-formed portions of cycloids as they continue to propagate. We have addressed this problem by analyzing cycloid characteristics and addressing growth mechanics in the context of observed features.

We conducted a survey of cycloids in most imaged regions of Europa (69 in total), characterizing morphologies, geometries, and likely mechanical behaviors during growth. We performed statistical analyses of a range of cycloid attributes such as cusp-to-cusp segment length, cusp angles, curvature, inflection location (skewness), and crack azimuth to either side of a cusp. Most attributes are normally distributed about a central mean value and show no preferred value as a function of geographic location, implying a self-similar process of development from a geometric standpoint. Our study indicates that there are three morphologic styles of cycloids (trough, ridge, and band cycloids), although an individual cycloid segment may change from one morphology to another along its curved trace. Furthermore, there are a range of morphologic styles of cusps (simple or complex), which commonly exhibit disparate morphology cycloid segments to either side of the cusp.

We measured the cusp angles (112 in total) between cycloid segments in an attempt to characterize the nature of cusps. Although these angles can vary widely across Europa (a range of 22° - 87° was observed), these angles are normally distributed about a median of 58°, which is very similar to the median angle of tailcracks along ridge-like faults, as described in the previous section. Furthermore, cycloid cusps bear a marked physical resemblance to tailcrack geometries, leading us to hypothesize that cusps do not develop through purely tensile crack growth to either side of the cusp (as suggested in the existing cycloid growth model), but instead may form analogous to tailcracks, thus requiring shearing along a pre-existing interface to create a near-tip perturbed stress field within which the tailcrack/cycloid cusp can develop. Such a scenario is completely compatible with the rotational characteristic of the diurnal tidal stress field, which would actually resolve shear stresses onto already-formed portions of developing cycloids.

We have thus developed an alternative model for the formation of cycloids that specifically considers the effects of resolved shear stress on cycloid segments, induced by the diurnal stresses as they rotate during the Europan day. Our model shows that the sense of shearing induced on an existing cycloid segment is always consistent with the direction of new cycloid segment growth (i.e., the cusp direction), which initiates in the form of a tailcrack before being driven by the rotating diurnal stress field. This model also explains the development of complex cusps, which show several new cycloid segments developing at a single cusp, but with only one becoming dominant and forming a complete cycloid segment. This phenomenon is analogous to horsetail splaying, meaning that a number of tailcracks cluster near the tip of a slipping interface. Such features are common in terrestrial strike-slip fault examples, and have also been identified along Europan strike-slip faults, including work completed during this project. Our shearing model can account for variability in segment curvature characteristics along a single cycloid chain because the amount of resolved shear on a propagating curved crack will dictate the ongoing degree of curvature as growth continues. The amount of shear stress varies with crack growth speed, which may very well be variable from one cycloid segment to the next. Finally, our model predicts differing amounts of shearing versus dilational reworking along the curved trace of a cycloid, which may explain the variability in surface morphologies. Differences in mechanical processes during fracture development (e.g., shearing versus dilation) have also been invoked in other published works to explain the range of lineament types on Europa (e.g., trough, ridges and bands).

In essence, our work on cycloid development has allowed a more finely honed understanding of the specifics of cycloid growth which, although perhaps controversial to proponents of the existing tension crack growth model, does provide a mechanically based rationale for the formation of cusps between cycloid segments that is reconcilable with the characteristics of the diurnal stress field.

(4) Crustal Thickness Estimates

The purpose of this goal was to examine the issue of thickness of the brittle ice shell of Europa (from the perspective of the ongoing thick-shell versus thin-shell argument), based on fracturing characteristics in regions of crustal bending. This aspect of the study resulted in 2 full-length papers (1 currently accepted and in revision, and 1 in preparation) and 2 conference presentations.

This aspect of the project was approached using a two-step process, both of which were geared towards capturing evidence for shell thickness as manifested by brittle deformation. The first technique involved the development of analytical models to quantify (through flexure analysis) the effects of ice plate bending beneath ridge line loads on Europa, which are mathematically definable and directly dependent on material properties and plate thickness. The second technique involved an examination of the effects of impact into an ice layer overlying a water layer, comparing terrestrial analogs involving explosion cratering on floating ice with Europan features potentially associated with impact events.

On Europa, downward deflections of the ice plate below many prominent ridges resulted in tensile bending stresses at the surface on either side of ridges and consequent surface fracturing. Similar phenomena have been previously described for loading of the ice shell around mounds and regions of chaos. The utility of identifying bending as the driving force behind cracking is that it provides an indication of the elastic thickness of the bending plate. We used reasonable estimates of ice elastic properties on Europa to calculate the brittle ice thickness. Our results indicate a brittle thickness of less than 3 km. Furthermore, brittle thickness does not appear to be homogeneous on Europa but rather varies as a function of the terrain type being crossed by the ridge that produces the vertical loading. For example, where ridges load band material, resultant cracks imply a crust at least 50% thinner than is implied by those cracks that form through the same process in ridged plains materials. The thickness of Europa's ice shell is thus likely to be spatially variable depending on the geologic history of a particular region. One caveat is that bending cracks only capture thicknesses at the time of bending; therefore, variability could conceivably be temporal too, although the ridges examined were all relatively young in the overall geologic sequence. Although our results indicate a relatively thin ice shell, it could be argued that a thick ductile ice layer underlies the thin brittle layer; a problem that, as yet, has no clearly identifiable solution.

To complement the bending analysis, we examined selected regions of impact craters, chaos, and micro-chaos on Europa and investigated the implications for impact mechanisms for their formation. We do not mean to imply that all chaos forms through impact, as diapirism is a very viable mechanism for the creation of many chaos and lenticulae on Europa. Nonetheless, many of the features we examined could conceivably have formed by an impactor. We compared terrestrial naval experiments on sea ice involving explosives to make qualitative estimates of ice thickness based on the morphology of the resultant crater. Many similarities were discovered between these terrestrial experiments and Europan features, with morphologic variability that indicates the possibility that the ice shell has a thickness that is either spatially or temporally variable, and is likely to be thin in places but thick in other areas (based on the characteristics of large crater morphologies). Although no definitive answer can be given as to the thickness of the shell, the variability in thickness is an important result that should be incorporated into future investigations into the spatially heterogeneous nature of deformation of the ice shell.

Finally, we considered the hypothetical scenario of ice breakage from below in response to an impact-induced sub-ice tsunami. Our calculations indicate that an ice shell of up to 6 km thickness could reasonably be broken by such an impact-generated wave. Furthermore, the predicted size of the ice rafts that would be created as a result of bending-related fracturing of the ice shell by the wave is not incompatible with observed ice raft sizes in some chaos regions examined. If such a mechanism created these rafts, it would indicate a relatively thin ice shell overlying a liquid ocean.

Research Summary

The work completed during the funding period has provided many important insights into fracturing behavior in Europa's ice shell. It has been determined that fracturing through time is likely to have been controlled by the effects of nonsynchronous rotation stresses and that as much as 720° of said rotation may have occurred during the visible geologic history. It has been determined that there are at least two distinct styles of strike-slip faulting and that their mutual evolutionary styles are likely to have been different, with one involving a significant dilational component during shear motion. It has been determined that secondary fracturing in perturbed stress fields adjacent to older structures such as faults is a prevalent process on Europa. It has been determined that cycloidal ridges are likely to experience shear stresses along the existing segment portions as they propagate, which affects propagation direction and ultimately induces tailcracking at the segment tip than then initiates a new cycle of cycloid segment growth. Finally, it has been established that mechanical methods (e.g., flexure analysis) can be used to determine the elastic thickness of the ice shell, which, although probably only several km thick, is likely to be spatially variable, being thinner under bands but thicker under ridged plains terrain.

Personnel

The personnel associated with the project were as follows:

Simon Kattenhorn (PI) – Associate Professor at UI and graduate student advisor
Sandra Billings – MS graduate student in geophysics at UI (December 2004 completion)
Scott Marshall – MS graduate student in geology at UI (August 2004 completion)
Louise Prockter (co-I) – research advisor to the project

Dissemination of Research Results

Papers

Billings, S.E., and Kattenhorn, S.A. 2005. The great thickness debate: Ice shell thickness models for Europa and comparisons with estimates based on flexure at ridges. In revision for publication in *Icarus* (Special Volume on Europa's Icy Shell).

Billings, S.E., and Kattenhorn, S.A. Impact into Europa's icy shell: Comparison with terrestrial experiments of explosions on floating ice and implications for ice thickness. In preparation for submission to *Icarus*.

Kattenhorn, S.A. 2004. Strike-slip fault evolution on Europa: evidence from tailcrack geometries. In press, *Icarus*.

Kattenhorn, S.A. 2002. Nonsynchronous rotation evidence and fracture history in the Bright Plains region, Europa. *Icarus* 157, 490-506.

Kattenhorn, S.A., and Marshall, S.T. Perturbed stress fields and secondary fracturing at fault tips in the ice shell of Europa are analogous to terrestrial faults. In preparation for submission to *Journal of Structural Geology*.

Marshall, S.T., and Kattenhorn, S.A. 2005. A revised model for cycloid growth mechanics on Europa: evidence from surface morphologies and geometries. In revision for publication in *Icarus* (Special Volume on Europa's Icy Shell).

Masters Theses

Billings, Sandra E. Analysis of the ice shell of Jupiter's moon Europa: Estimation of the ice thickness and an examination of impact effects into a floating ice shell. University of Idaho, Moscow, Idaho, U.S.A.

Marshall, Scott Thomas. Growth mechanics and morphologic evolution of cycloids on Europa. University of Idaho, Moscow, Idaho, U.S.A.

Conference Abstracts

Billings, S.E., and Kattenhorn, S.A. 2003. Comparison between terrestrial explosion crater morphology in floating ice and Europan chaos. *Lunar and Planetary Science Conference Abstracts* XXXIV, #1955.

Billings, S.E., and Kattenhorn, S.A. 2002. Determination of ice crust thickness from flanking cracks along ridges on Europa. *Lunar and Planetary Science Conference Abstracts* XXXIII, 1813.

Kattenhorn, S.A. 2004. What is (and isn't) wrong with both the tension and shear failure models for the formation of lineae on Europa. *Abstracts, Workshop on Europa's Icy Shell*, #7023, Lunar and Planetary Institute, Houston, Texas, February 2004.

Kattenhorn, S.A. 2003. Secondary fracturing of Europa's crust in response to combined slip and dilation along strike-slip faults. *Lunar and Planetary Science Conference Abstracts* XXXIV, #1977.

Kattenhorn, S.A., and Marshall, S.T. 2003. Secondary fracturing as a tool for unraveling strike-slip fault slip behavior on Europa. *Eos, Transactions of the American Geophysical Union* 84.

Kattenhorn, S.A., and Billings, S.E. 2002. Linear Elastic Fracture Mechanics (LEFM) analysis of crustal deformation on Europa with comparisons to terrestrial analogs. *GSA Abstracts with Programs* 34(6).

Marshall, S.T., and Kattenhorn, S.A. 2004. Analysis of Europan cycloid morphology and implications for formation mechanisms. *Abstracts, Workshop on Europa's Icy Shell*, #7026, Lunar and Planetary Institute, Houston, Texas, February 2004.

Marshall, S.T., and Kattenhorn, S.A. 2004. The importance of resolved shear stress and dilation at the instant of cycloid cusp formation on Europa. *AGU Annual Fall Meeting*, San Francsico, December 2004.

Marshall, S.T., and Kattenhorn, S.A. 2003. Secondary normal faulting near the terminus of a strike-slip fault segment in the Lake Mead fault system, SE Nevada. *Eos, Transactions of the American Geophysical Union* 84.

Invited Seminars

Lunar and Planetary Institute, Houston, Texas. Invited to present at the LPI colloquium series, May 2003. Title of presentation:

"Breaking the ice: Europa's enigmatic crust."

Future Prospects

A follow-up proposal for continued NASA funding was submitted to PG&G in May 2004 requesting funding for a project that will focus on the mechanical origins of ridges and strike-slip faults, as well as a comprehensive classification of strike-slip fault types and displacement characteristics. Funding decisions for this grant submission cycle are still pending.