IUTAM Symposium on Scaling Laws in Ice Mechanics and Ice Dynamics

SOLID MECHANICS AND ITS APPLICATIONS
Volume 94

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The median level of presentation is the first year graduate student. Some texts are monographs defining the current state of the field; others are accessible to final year undergraduates; but essentially the emphasis is on readability and clarity.

For a list of related mechanics titles, see final pages.

IUTAM Symposium on

Scaling Laws in Ice Mechanics and Ice Dynamics

Proceedings of the IUTAM Symposium
held in Fairbanks, Alaska, U.S.A.,
13–16 June 2000

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CONTENTS

PREFACE

This Volume constitutes the Proceedings of the IUTAM Symposium on 'Scaling Laws in Ice Mechanics and Ice Dynamics', held in Fairbanks, Alaska from 13th to 16th of June 2000. Ice mechanics deals with essentially intact ice: in this discipline, descriptions of the motion and deformation of Arctic/Antarctic and river/lake ice call for the development of physically based constitutive and fracture models over an enormous range in scale: 0.01 m - 10 km. Ice dynamics, on the other hand, deals with the movement of broken ice: descriptions of an aggregate of ice floes call for accurate modeling of momentum transfer through the sea/ice system, again over an enormous range in scale: 1 km (floe scale) - 500 km (basin scale).

For ice mechanics, the emphasis on lab-scale (0.01 - 0.5 m) research contrasts with applications at the scale of order 1 km (ice-structure interaction, icebreaking); many important upscaling questions remain to be explored. In ice dynamics, the general opinion is that continuum mechanics and rheological models can be used at scales above 10 km. While elastic-plastic and viscous-plastic macroscopic laws provide satisfactory results at climatological scales, attempts to downscale these models have met with less success regarding time scales of the order of a day and regional scales (50 km). Apparently, rheological models must be properly chosen for the scale of interest. Reliable rheological models that can accurately describe the internal resistance of an aggregate of ice floes at various scales are currently lacking, as is the ability to downscale and interface with knowledge at the scale of 1 km. Direct numerical simulation techniques developed in the granular flow community have been applied successfully to model the surface transport of ice in rivers, as well as to explain the physical process of ridging in the Arctic. However, the description of mesoscale and geophysical scale processes based on these techniques is far from developed. Clearly, what science is done is set by an individual's decision to work at a certain scale. Intuitively, the study of ice is divided into the analysis of subsets of processes based on scale and their interactions with adjacent scales. However, the methodologies applied at each scale differ hugely, with little communication downscale or upscale. Certainly, the relative merits, limits and deficiencies of the approaches at each scale are not well understood.

The objective of the proposed symposium is to bring together researchers who have made significant contributions at various scales in the study of ice, and those who have made significant contributions to the mechanics of heterogeneous media in other fields. At this time, there is no clear guidance as to the range of applicability of different constitutive laws, and a lack of ability to link the behavior at smaller scales (the scale of the discrete phase) with successive geophysical scales. The aim is to ignite a process that will integrate these areas, so that an organized approach to understand the scaling problem can be established in the ice mechanics and ice dynamics community. There is every possibility that the mechanics community can play a major role in this development.

The symposium consisted of 36 lectures, all of which were invited and accorded equal weight in the program. In addition, a number of poster boards, which were set up for the duration of the symposium, allowed a further 12 invited presentations. The content of 33 of the lectures and six of the poster presentations are included in this volume.

The International Scientific Committee responsible for the Symposium comprised the following:

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Dr. R. V. Gol'dstein (Russia)
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The Committee gratefully acknowledges financial support for the Symposium from the International Union of Theoretical and Applied Mechanics (IUTAM), the United States Army Research Office (ARO), Department of the Interior (DOI), National Science Foundation (NSF) and Office of Naval Research (ONR), BP Amoco (BP), and the International Arctic Research Center, University of Alaska Fairbanks (IARC). In this context, let it be noted that the views, opinions, and/or findings contained in this book are those of the authors and should not be construed as an official ARO, BP, DOI, IARC, IUTAM, NSF or ONR position, policy, or decision, unless so designated by other documentation.

The smooth running of the Symposium owes much to the unstinting efforts of the sole member of the local organizing committee, Dr. L.H. Shapiro, Geophysical Institute, University of Alaska Fairbanks.

THE ICY CRUST OF THE JUPITER MOON, EUROPA

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Abstract Solar system exploration shows a wide variety of satellites with icy surfaces. Europa, a moon of Jupiter, is a rocky object about the size of Earth's moon, but covered with an outer shell of water composition 150 km thick. Although the surface is frozen, it is not known if liquid water exists beneath the icy crust. Surface evidence suggests the presence of water or mobile ice in the recent past; images reveal slabs of crust that have been disrupted and moved into new positions. Other areas show zones that have been fractured, spread apart, and infilled by water-rich material. Various ice ridges, some more than 2000 km long, could represent fractures of the ice in response to tidal stresses, followed by extrusion of ductile ice or water, or they could be intrusions of thermally-driven ductile ice, or features resulting from some other process. Although some features are similar to those of terrestrial sea ice, their large size and morphology require additional explanations. This report reviews the current understanding of Europa's ice crust and outlines plans for future exploration.

1. Introduction

Jupiter's moons were discovered by Galileo Galilei in 1610 using the newly invented telescope. Since then, improvements in telescopes have continued to provide insight into these remarkable worlds. The first clues to the characteristics of Europa's surface came with the *Voyager 1* and *2* flybys of Jupiter in 1979 [Smith et al., 1979a, b]. The best pictures of Europa had resolutions of only about 1.9 km/pixel, enabling preliminary geological assessments [Lucchitta and Soderblom, 1982; and Malin and Pieri, 1986]. Since 1995, the *Galileo* spacecraft has been in orbit around Jupiter and has made repeated flybys of Europa, returning geophysical measurements, images of the surface in resolutions as high as 6 m/pixel, and other remote sensing information.

Europa is a rocky object about the size of Earth's moon. Tracking of the Galileo spacecraft during close flybys enabled estimation of Europa's axial moment of inertia which suggest various models of the interior, including a three-layer configuration of an outer H_2O layer 80 to 200 km thick, an intermediate rocky mantle, and an inner core composed of iron and iron sulfide [Anderson et al., 1998]. The total water in the shell exceeds the volume of all of Earth's oceans. With equatorial temperatures of 110 k and polar temperatures of 50 k, the outer shell of this water is frozen. Remote sensing observations of Europa's surface reveals the presence of such ice, but with non-ice materials, such as salts and sulfur compounds, also occurring as local patches [Carlson et al., 1999; Fanale et al., 1999].

J.P. Dempsey and H.H. Shen (eds.),
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Europa and its neighboring moons orbit Jupiter in a systematic pattern; Io, the innermost moon, orbits Jupiter every 1.8 Earth days, while the next satellite outward, Europa, takes twice as long to orbit Jupiter (3.6 days) and Ganymede, the outermost of the three, orbits Jupiter in 7.2 Earth days. This pattern, known as a *Laplace resonance*, causes the satellite orbits to be non-circular and for the gravitational attraction toward Jupiter to vary. In response to these variations, tides are generated within the satellites, leading to internal friction and the generation of heat. In the case of Io, there is sufficient heat to form magma, driving active volcanoes. Calculations for Europa suggest that there is sufficient heat to melt the ice or to prevent its freezing from an initial liquid state dating from the formation of the satellite [Cassen et al., 1982].

The Galileo magnetometer revealed the presence of a magnetic field around Europa induced by Jupiter [Khurana et al., 1998]. Although there are several possible explanations for the field, one plausible model includes the presence of a conducting layer of salty water beneath the icy crust [Kivelson et al., 2000]. However, other models include solid ice and it is not known definitively if liquid water exists today between the icy crust and the rocky interior (Fig. 1). Despite this uncertainty, images of Europa's surface show features which appear to be best explained by a relatively thin ice shell underlain by liquid water, slush, or convecting ice at the time of their formation [Greeley, 1997; Greeley et al., 1998a,b; Pappalardo et al., 1999].

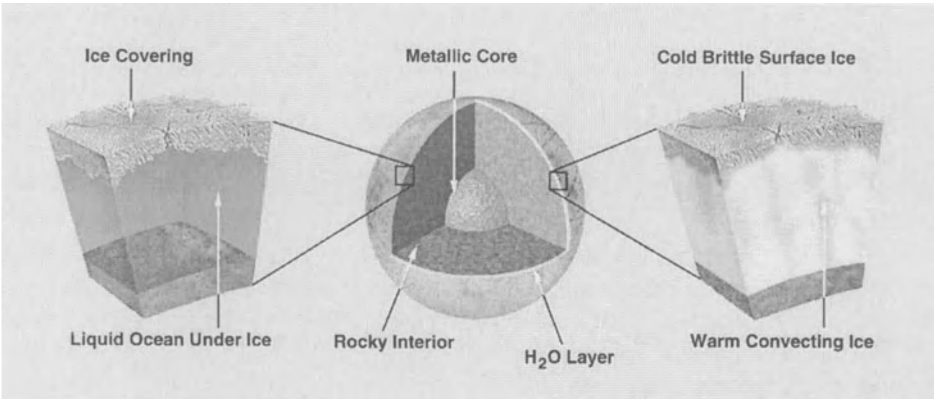

Figure 1. Diagrams showing possible interior configuration for Europa; the outer H_2O layer could include a liquid "ocean" overlain by an ice layer (left side), or the H_2O layer could be completely frozen to the rocky mantle, but could also include a zone of convecting ice (right side) (NASA PIA 01669).

2. General Surface Characteristics

Europa is in synchronous or near-synchronous orbit around Jupiter; like Earth's moon, it shows the same hemisphere toward its parent. Terms to describe Europa include the *sub-Jovian hemisphere,* which faces Jupiter; the *leading hemisphere*, which is the side facing the direction of motion by Europa in its orbit around Jupiter; the *anti-Jovian hemisphere* (the side facing away from Jupiter), and the *trailing hemisphere.*

Global views of Europa in color show a bright object with brownish mottled patterns in some areas, especially on the trailing hemisphere [McEwen, 1986]. Bright plains tend to dominate the leading hemisphere. Analysis of Voyager data led to the hypothesis that the bright plains resulted from flooding of the surface by liquid water erupted from the sub-surface and which subsequently froze. The trailing hemisphere tends to be darker because there is a greater abundance of mottled zones on the surface. Prior to the Galileo mission, one explanation for the dark patches was that this hemisphere received implantation of non-ice materials from external sources. Although one might expect the leading hemisphere to be a better candidate for such implantation, Europa is immersed in Jupiter's magnetosphere which carries with it various charged particles, such as sodium ions. Because the velocities of these particles are higher than Europa's orbit around Jupiter, they potentially can 'catch-up' with Europa and preferentially impact the trailing side.

Cross-cutting Europa's surface are linear features 100s of kilometers long in a pattern likened to string wrapped around a baseball. The global patterns formed by these features and seen on *Voyager* images were used by some investigators (e.g. Helfenstein and Parmentier, 1983, 1985) to interpret patterns of stress in Europa's icy shell.

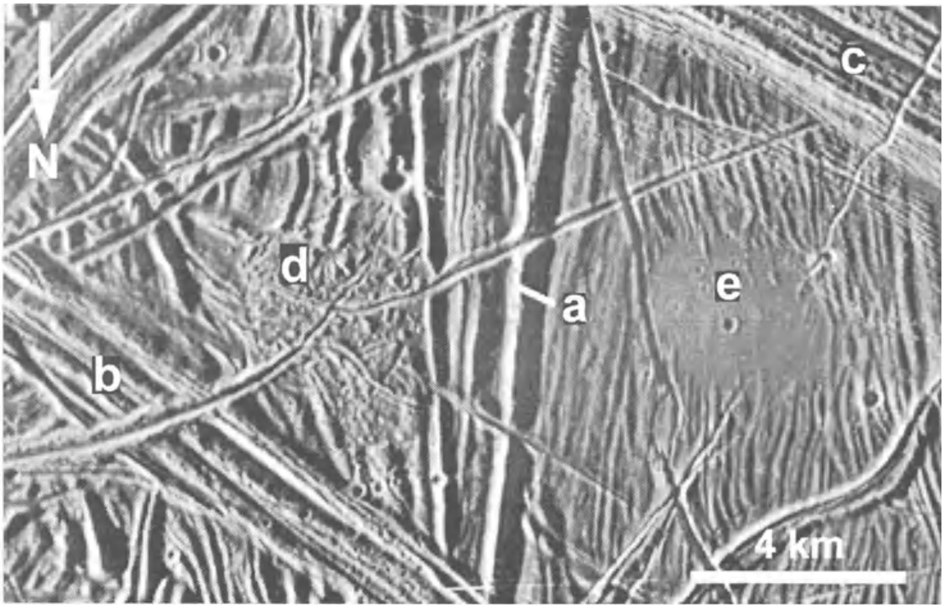

Figure 2 . Galileo image showing complex ridged plains in the trailing hemisphere of Europa (illumination from the left); visible are a) large single ridge some 100 m high, b) double ridge separated by a groove, c) complex ridge and groove system, d) chaos terrain, and e) area that appears to have been flooded. The small craters, including the crater in the middle of the inferred flooded zone, are considered to be impact structures. Cross-cutting relations enable the sequence of ridge and trough formation to be determined. (area shown is 11 by 16 km; north is to the bottom; Galileo image s0374685452, resolution 26 m/pixel).

3. Surface Features

3.1 Ridges

Various ridges constitute the most common types of features on the surface. Some ridges exceed 2000 km in length. They range in width from ~10-20 m to more than 10 km and can be several hundred meters high. Ridges vary in morphology from single structures, to double ridges separated by a narrow depression, to complex sets of ridges and grooves (Fig. 2). High resolution images show that the flanks of some ridges include icy, mass wasted material. Many ridges are darker and somewhat brown in comparison to the terrain in which they occur; however, the dark brown zone is not confined to the ridges but extends outward from the ridge flanks, blending with the surrounding terrain with no clear outer boundary [Clark et al., 1998]. Some ridges are flanked by approximately parallel fractures, suggesting cracking of the ice as a consequence of "loading" by the weight of the ridge [Greeley et al., 1998a]. In other cases, layering in the surrounding ice appears to bend upward on the flanks of the ridge.

Various mechanisms have been proposed to explain how ridges form. These include: 1) explosive eruptions of gas-driven material and the accumulation of icy "pyroclastic" deposits, 2) extrusions of slush or ductile ice through fractures, 3) upwarping of the crust in response to intrusions [Head et al., 1999], and 4) structurally-driven mechanisms such as thrust-faulting, perhaps accompanied by extrusion of subsurface materials [Greenberg et al., 1998]. However, it is difficult in most of these mechanisms to account for the uniform width and height of the ridges extending over their great lengths. The dark zones associated with many ridges could be mantling deposits associated with explosive venting or, lag deposits of non-ice materials left as a consequence of heating which drove off the volatile components in the crust [Fagents et al., 2000].

Regardless of the mode of formation, cross-cutting relations enable the ridge orientations to be mapped through time. Nearly all models for formation require an initial fracture and it is assumed that the fractures form in response to a stress field. Consequently, the ridge patterns can be compared to global geophysical models of Europa. As reviewed by Pappalardo et al. [1999a,b], these models include global expansion of Europa as the water layer froze and the surface fractured, various stresses developed in response to tidal action, and stresses resulting from possible non-synchronous rotation of Europa in its orbit around Jupiter. Geissler et al. [1998a,b], Greenberg et al. [1998], and Figueredo and Greeley [2000] suggest that there has been a systematic shift in ridge orientations through time. The pattern is consistent with a model in which Europa is in non-synchronous rotation; in this case the rocky interior moves at a different rate than the icy outer shell, causing distinctive fractures.

Particularly intriguing are the cycloidal ridges (Fig. 3). Modeling by Hoppa et al. [1999] suggests that each cuspate segment resulted from the propagation of a fracture in a rotating stress field during a single orbit. The process is repeated during successive orbits to produce a cycloidal lineament.

3.2 Ridged plains

Bright plains constitute the most widespread terrain and were imaged by Galileo. In contrast to earlier interpretations based on low resolution images, there are no indications of flooding by widespread flows. Instead, the plains consist primarily of complex sets of ridges and grooves (Fig. 2), and are among the oldest terrains on Europa. The topographic relief of these features is generally lower than that seen on individual ridges described in Sec. 3.1. Whether the lower relief represents viscous relaxation of the ice through time, or some fundamental difference in ridges formation earlier in Europa's history is not resolved.

3.3 Bands

Wide linear surface features, such as *wedge-shaped bands* (Fig. 4), commonly are distinguished by low albedos and textures oriented parallel to the strike of the bands. The bands often exhibits bilateral symmetry, usually centered on a medial trough [Sullivan et al., 1998]. Such bands might be comparable in some ways to sea-floor spreading on Earth, in which the crust is repeatedly separated and infilled with material from the subsurface. High resolution images show that the Europan bands are complex, with smaller bands cross cutting or 'splaying' into or out of the larger bands. Thus, the formation of banded terrain is more complicated than simple crustal spreading and infilling. In some cases, lateral shear, or strike-slip motion, appears to have contributed to the formation of banded terrain [Tufts et al., 1999].

Figure 3 . View of cuspate-shaped features called *cycloidal ridges*, which might result from stress pattern imposed in the icy crust as a consequence of tides [Hoppa et al., 1999]. The feature shown in the middle of this image is more than 450 km long and is about 1.5 km wide. Europa's horizon is visible in the upper left. (Galileo image s0449974427).

3.4 Lenticulae

Dark spots as large as ~10 km across occur in many areas of Europa. Termed *lenticulae,* they vary in morphology including low-relief surface "welts," domes with summit fractures, local flowlike structures, and zones where the icy crust has been disrupted (Fig. 4). In some areas, lenticulae are closely spaced and merge into larger areas of chaos terrain. Lenticulae probably have more than one mode of formation, including upwarping from subsurface convection or diapiric activity [Pappalardo et al., 1998], melt-through of the ice crust from local concentrations of heat [Greenberg et al., 1999], and extrusion of icy slush from the subsurface [Figueredo and Greeley, 2000].

Some lenticulae are surrounded by moatlike depressions, suggesting "loading" of the ice crust. Based on this assumption, flexural models were applied to determine the thickness of the elastic icy lithosphere; the results suggest a thickness of <100 - 350 m at the time of assumed deformation [Williams and Greeley, 1998].

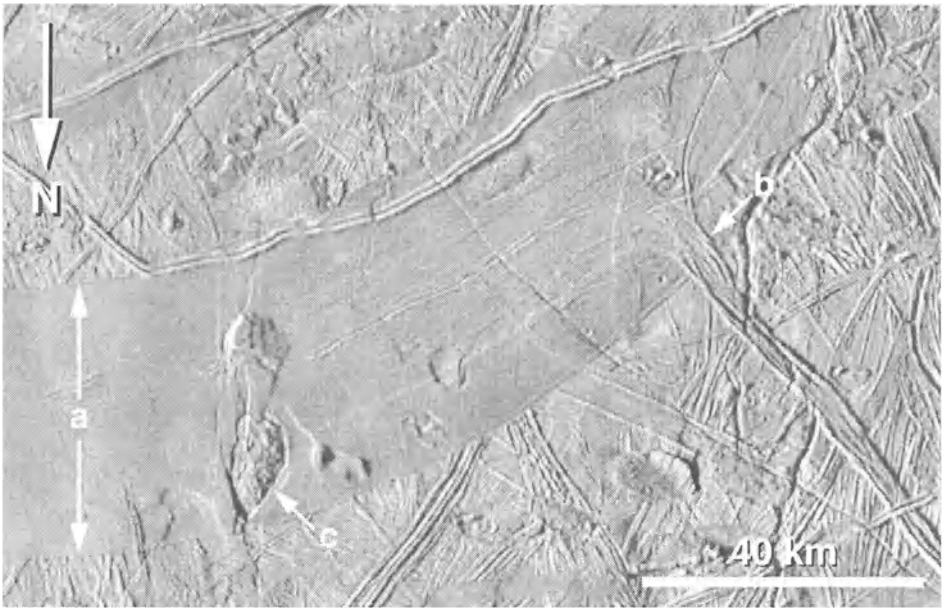

Figure 4 . Wedge-shaped bands (a) generally are darker and smoother than the terrains in which they occur; ridge and ridge-groove terrain (b) can cut into (or out of) wedge-shaped bands; also visible are lenticulae (c) which appears to have formed by the disruption of the band material. Illumination is from the left, north is to the bottom; area shown is 85 by 133 km (ASU IPF 1108).

3.5 Chaos Terrain

One of the key Galileo mission discoveries is the existence of areas that have resulted from crustal disruption [Greeley, 1997; Carr et al., 1998] forming *chaos terrain.* In these areas (Fig. 5), the icy crust has been broken into segments which were rafted apart like pieces of a jigsaw puzzle [Greeley et al., 1998a; Spaun et al., 1999]. The occurrence of chaos terrain is widespread, having been found in equatorial areas and both polar regions. Although this would suggest that the ice shell is globally thin, the absence of chaos terrain in some areas could mean that the shell is not of uniform thickness.

The areas between the ice segments, or plates, are generally at a lower elevation and consist of hummocky terrain (the "chaos") although some areas of chaos are high-standing. In some cases, ice blocks have been tilted from their original horizontal positions and appear to be partly submerged, analogous in some respects to icebergs.

In general, the chaos matrix in which the segments reside is darker than the surrounding terrain and is brownish. In the initial analyses of the Galileo data [Belton et al., 1996], it was assumed that the underlying mobile zone was a different composition than the ice crust. However, we now see that the brown appearance also applies to some of the disrupted plates and can extend into the surrounding plains. Thus, while it is still thought that the subsurface material contains a higher proportion of dark, non-water components than the surface materials, the surface might also contain lag deposits from which the volatile components have been lost, similar to the mechanisms described to explain the dark brown zones associated with some ridges.

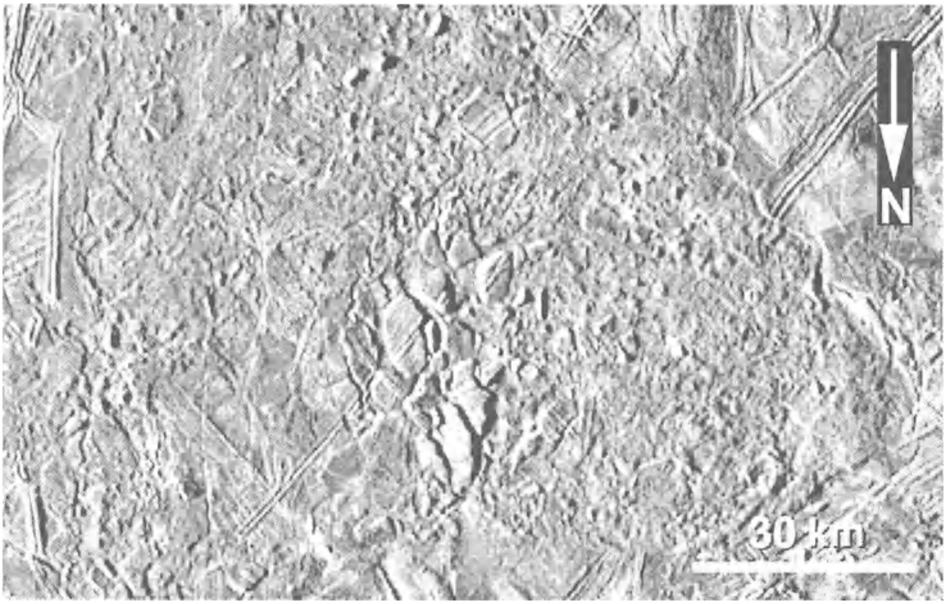

Figure 5 . *Chaos terrain* appears to form at the expense of the ridged plain (upper right); note the segments of ridged plains (lower middle) that have been only partly broken apart. Illumination from the left, north to the bottom; area shown is 90 by 130 km (ASU IPF 1108).

The dimensions of the smaller displaced segments in chaos terrain and the degree of displacements suggests that the disruptions occurred over highly mobile ice, if not slush or liquid water. If this is the case, then the widespread occurrence of chaotic terrain suggests that the subsurface zone enhancing the disruption was global in extent.

Regardless of the details of chaos terrain formation, its discovery has stimulated new considerations of a global subsurface "ocean" of liquid water beneath the ice [Carr et al., 1998]. Pappalardo et al. [1999 a, b] reviewed the evidence and concluded that a definitive answer cannot be formulated at this time. It is noted, however, that results from the Galileo magnetometer are consistent with a model involving an electrically conductive subsurface zone, such as salty water [Kivelson et al., 2000].

3.6 Impact structures

Fewer than a half dozen features were identified on Voyager images as impact craters on Europa. This led to speculation that its surface was geologically very young (superposed impact crater frequencies provide a measure of the age of surface formation; the more craters, the greater the age, as proven from studies of Earth's moon). Galileo images show that impact craters are preserved on Europa, although the frequency is still very low in comparison to most other planets and satellites. Attempts have been made to determine the age(s) of different surface units on Europa through the extrapolation of crater frequencies for lunar surfaces that have been 'calibrated' by radiogenic dates from lunar samples. Unfortunately, the extrapolations to Europa have great uncertainties and the age estimates for the surface range from <10 million years to nearly a billion years [Neukum, 1997]. It is unlikely that this uncertainty in age will be reduced until there is better knowledge of the impact cratering history in the Jovian system.

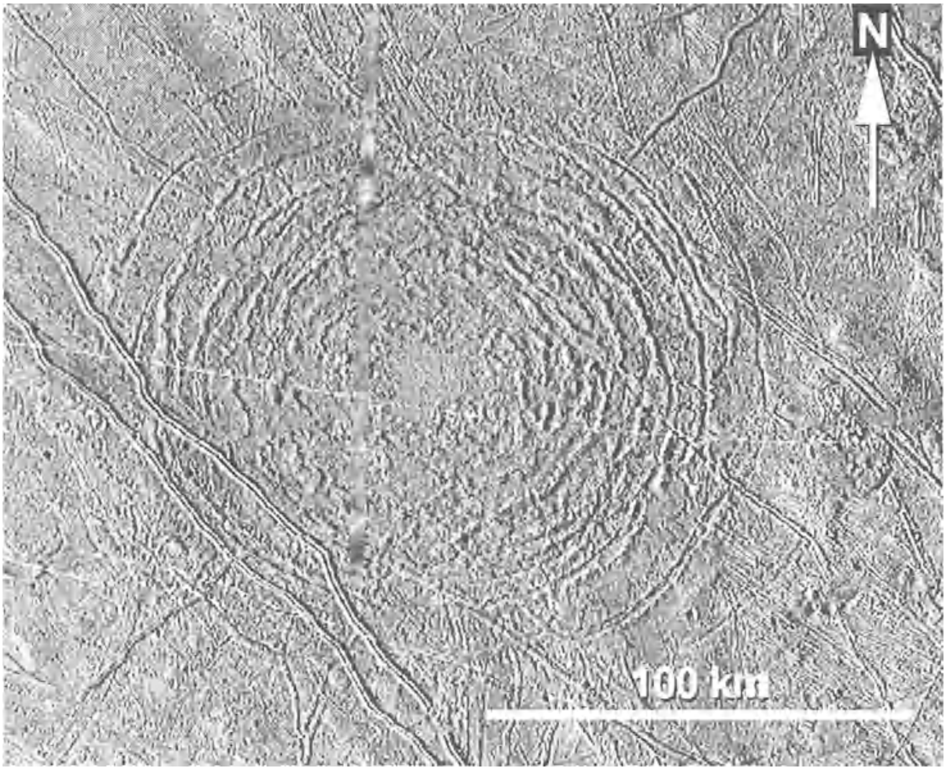

Figure 6 . Mosaic of Galileo images showing *Tyre*, an impact structure identified by concentric fractures and grabens defining a diameter some 150 km across; the morphology of this structure suggests that the impact occurred in a thin , brittle ice crust underlain by slush or liquid water at the time of the impact, illumination from the left, north to the top; area shown is 200 km by 175 km (Galileo image mosaic ASU-IPF 1122).

As shown in Figure 6, large impact structures on Europa have very low topographic relief [Moore et al., 1998]. This is attributed to either target properties at the time of impact or to viscous relaxation of topographic features formed in ice, or a combination of these two possibilities. In the first case, some models suggest that impacts penetrated through a thin brittle crust into underlying slush or liquid water, or that the impact melted the ice locally [Greeley et al., 1998a]. The morphology of the larger impact features probably represents penetration through a brittle ice shell some 5-10 km thick underlain by less competent material at the time of the impact [Moore et al., 1998].

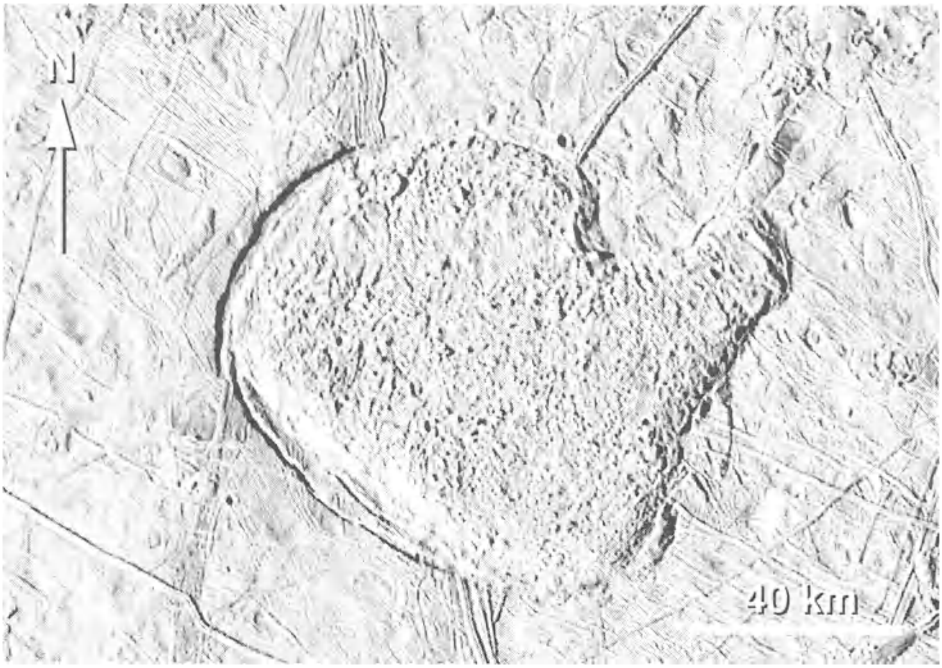

Figure 7. This feature, informally referred to as *the mitten* because of its outline, consists of chaotic terrain that is elevated above the surrounding ridged plains and is thought to have formed by extrusion of slush from the subsurface and emplacement by flow. Illumination is from the lower left, north is to the top; area shown is 130 by 185 km (Galileo frame s0449974300, resolution 270 m/pixel).

Many of the Europan craters show dark deposits on their floors which have spectral properties similar to the dark deposits found elsewhere on Europa and presumed to come from the subsurface. Near infrared mapping spectometer (NIMS) data suggest that this dark material contains various non-ice components, including salts such as magnesium sulfate [Carlson et al., 1999; Fanale et al., 1999; McCord et al., 1998] and sulfur - containing compounds [Carlson et al., 1999].

3.7 Flowlike features

In contrast to expectations prior to the Galileo mission, very few features have been identified that are clearly the result of extrusions of liquids onto the surface. Possible candidates include some lenticular and some features such as *Thrace Macula* [Wilson et al., 1997], an irregular shaped zone of chaos which includes dark deposits which embay and mantle the older surrounding terrain. Other possibilities include small (~3 to 4 km across) dark, smooth areas (Fig. 2) which appear to represent local flooding or in situ melting [Greeley, 1997], and some domical structures, such as *the mitten* (Fig. 7).

4.0 Summary and Conclusions

The images from the Galileo SSI experiment show Europa to be a far more intriguing object than was suspected previously. Among the significant findings are: 1) the discovery of widespread chaos terrain, suggesting disruption and possible melting of a brittle icy crust, underlain by a mobile zone of ice, slush or water, 2) the formation of the bright terrain by tectonic processes and the lack of widespread flooding of the surface by flows, and 3) ridge patterns that suggest non-synchronous rotation of Europa and deformation, some of which might result from daily tidal action. Collectively, these results and others suggest that Europa once had a global-scale subsurface zone of highly mobile ice, slush, or even liquid water. Whether such a zone exists today must await future exploration. Present plans call for a spacecraft, the *Europa orbiter*, to be launched in 2003 for a journey that would place it in operation in 2008 for the purpose of mapping the entire surface of Europa in high resolution (~250 - 300 m/pixel) and to map its precise shape as a function of daily tides.

Acknowledgments

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